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Optimal entropy squeezing sudden generation and its control for an effective two-level moving atom entanglement with the two-mode coherent fields*

Liu Xiao-Juan(刘小娟)[a)c)†], Zhou Yuan-Jun (周元俊)[b)], and Fang Mao-Fa(方卯发)[c)]

[a)] *Department of Physics, Hunan University of Science and Technology, Xiangtan* 411201, *China*
[b)] *Department of Physics, Nanjing University, Nanjing* 210093, *China*
[c)] *Department of Physics, Hunan Normal University, Changsha* 410081, *China*

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From the viewpoint of quantum information, this paper proposes a concept and a definition of the atomic optimal entropy squeezing sudden generation (AOESSG) for the system of an effective two-level moving atom which entangles with the two-mode coherent fields. It also researches the relationship between the AOESSG and entanglement sudden death of the atom-fields, and discusses the influences of atomic initial state on the AOESSG and obtains the system parameter which controls the AOESSG.

Keywords: optical entropy squeezing sudden generation, effective two-level moving atom, entanglement sudden death

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1. Introduction

Recently, theories and experiments of quantum information processes (QIP) and quantum computers (QC) have become the subject of intense studies due to their unparalleled superiority over their classical counterparts.[1,2] The main obstacle of experimental realization of the QIP and QC is quantum noise (QN), which will cause distortion of the encoded quantum state and lead to decoherence of the QC.[3] Research has shown that the generation of a squeezed light is an effective way of inhibiting QN.[4]

On the other hand, over the past decade, there has been a great deal of interest in the two-level atomic squeezing owing to its potential application in the field of quantum optics.[5,6] Moreover, it has been shown that squeezed atoms can radiate a squeezed light,[4] which has recently been applied to quantum information theory, for example in quantum teleportation,[7,8] cryptography,[9,10] and dense coding,[11] and has become a focus of study.[12] Because an atomic optimal squeezing state corresponds to a quantum state with minimum noise, its generation and control are very important tasks in this research field. Usually studies of atomic squeezing are based on the Hesienbeg uncertainty relation (HUR) which is based on the variance of the system observations. But, the HUR cannot give us sufficient information on atomic squeezing in cases such as those as shown in Ref.[13]. Several authors[14,15] obtained an entropic uncertainty relation (EUR) for position and momentum which can overcome the limitation of the HUR. One of the authors of this paper in Ref.[13] has presented EUR for the two-level atom and defined the entropy squeezing for the two-level atom by using the quantum information theory. More recently, much work on atomic information entropy squeezing in one-photon and nonlinear multiquantum Jaynes–Cumming models was reported.[16−18] However, little attention has been paid to the atomic optimal entropy squeezing sudden generation (AOESSG) and its control for an effective two-level moving atom entangled with the two-mode coherent fields, which are to be studied in this paper by using the quantum information entropy theory. We will give a definition of the AOESSG, research into the relation between the AOESSG and entanglement sudden death of the atom-fields (ESDAF), discuss the influences of the atomic initial state on

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†Corresponding author. E-mail: lxjdx@163.net

the AOESSG and obtain the system parameters which control the AOESSG. Since the AOESSG can inhibit quantum noise instantly in the quantum information process and quantum computer, our results may be important for experimental realization of the preparation of the AOESSG and effective control of quantum noise in quantum information process and quantum computers.

2. The model and its solution

The model considered here is an effective two-level moving atom interacting with the two-mode fields via two-photon transitions. If we ignore the Stark shifts of the intermediate states, and consider atomic motion, we can write down a rotating-wave approximation Hamiltonian for the process as[19,20]

$$H = \omega_0 S_z + \sum_{j=1}^{2} \omega_j a_j^\dagger a_j + g f_1(vt) f_2(vt)(a_1^\dagger a_2^\dagger S_- + S_+ a_1 a_2), \quad (1)$$

where S_i $(i = z, +, -)$ is the usual pseudo-spin operator of the two-level atom, $a_j^\dagger$ (a_j) is the photon creation (annihilation) operator of the field mode of frequency w_j $(j \equiv 1, 2)$ and ω_0 represents the atomic transition frequency between upper state $|a\rangle$ and lower state $|b\rangle$; g is the coupling constant between the atom and the two-mode coherent fields, and $f_i(vt)$ $(i = 1, 2)$ denotes the mode structure of the i-th-mode coherent fields. We restrict our studies in the atomic motion along the z axis so it would be necessary for the z-dependence of the field-mode function to be taken into account. A $\mathrm{TEM}_{\mathrm{mnp}}$ mode is defined by[21]

$$f_i(vt) = \sin\left(\frac{p_i \pi v t}{L}\right), \quad (2)$$

where p_i represents the number of half-wave length of the i-th field mode inside a cavity of the length L.

For simplicity, we consider the two-photon resonance case, that is $\omega_0 = \omega_1 + \omega_2$, and the case $p_1 = p_2 = p$, the atom enters and leaves it after passing p half-wavelengths of electric field. Using the standard techniques,[21] in the interaction picture and in two-dimensional atomic space, we can write the time evolution Dyson operator as

$$U_I(t) = \begin{bmatrix} \hat{C} & -\mathrm{i}a_1 a_2 \hat{D} \\ -\mathrm{i}a_1^\dagger a_2^\dagger \hat{S} & \hat{T} \end{bmatrix}, \quad (3)$$

where

$$\begin{aligned} \hat{C} &= \cos(\hat{A} g \theta(t)), \qquad \hat{D} = \frac{\sin(\hat{B} g \theta(t))}{\hat{B}}, \\ \hat{T} &= \cos(\hat{B} g \theta(t)), \qquad \hat{S} = \frac{\sin(\hat{A} g \theta(t))}{\hat{A}}, \\ \hat{A} &= \sqrt{(a_1 a_2 a_1^\dagger a_2^\dagger)}, \quad \hat{B} = \sqrt{(a_1^\dagger a_2^\dagger a_1 a_2)}, \\ \theta(t) &= \int_0^t [f(vt')]^2 \mathrm{d}t' \\ &= \int_0^t \left[\sin\left(\frac{p\pi v t'}{L}\right)\right]^2 \mathrm{d}t' \\ &= \frac{1}{2}\left[t - \frac{L}{2p\pi v t}\sin(2pgt)\right]. \end{aligned} \quad (4)$$

At any time $t > 0$ the density operator of the system is given by

$$\rho(t) = U_I(t)\rho(0)U_I^\dagger(t), \quad (5)$$

where

$$\rho(0) = \rho_A(0) \otimes \rho_F(0), \quad (6)$$

$\rho_A(0)$ and $\rho_F(0)$ are the density operators of the atom and two-mode coherent field at $t = 0$, respectively. We consider two cases of the initial atom in pure states and mixed states: first, let $\rho_A(0)$ be in the following pure states

$$\rho_A(0) = \frac{1}{1+S^2}\begin{bmatrix} 1 & S\exp(-\mathrm{i}\varphi) \\ S\exp(\mathrm{i}\varphi) & S^2 \end{bmatrix}, \quad (7)$$

where, $0 < \varphi < 2\pi$ denotes the phase of the atom dipole, $S = 0, 1$. When $S = 1$, the atom is in a coherent superposition pure state $\frac{1}{\sqrt{2}}(|\, b\rangle + \exp(\mathrm{i}\varphi) \mid a\rangle)$; when $S = 0$, the atom is in a pure state $|\, b\rangle$.

Second, when $\rho_A(0)$ is in the following mixed states:

$$\rho_A(0) = \begin{bmatrix} \eta_1 & 0 \\ 0 & \eta_2 \end{bmatrix}, \quad (8)$$

i.e. $\rho_A(0) = \eta_1|b\rangle\langle b| + \eta_2|a\rangle\langle a|$, $\eta_1 + \eta_2 = 1$, $\eta_i \neq 0$ $(i = 1, 2)$. Let $|\eta_1 - \eta_2|$ represents the difference between atomic energy probability, in this case if $|\eta_1 - \eta_2| = 0$, the atom is in the maximal mixed state; if $0 < |\eta_1 - \eta_2| < 1$, the atom is in general mixed state.

Suppose that the initial field is in the two-mode coherent state,

$$\begin{aligned} |\, \psi_F(0)\rangle &= |\, \alpha_1, \alpha_2\rangle \\ &= \sum_{n_1, n_2 = 0}^{\infty} F(n_1)F(n_2) \mid n_1, n_2\rangle, \\ F(n_j) &= \exp\left(-\frac{\bar{n}_j}{2}\right)\frac{\alpha_j^{n_j}}{\sqrt{n_j!}}, \end{aligned} \quad (9)$$

where $0 < \xi < \pi$, ξ denotes the atomic distribution, $\alpha_j = \sqrt{\bar{n}_j}\exp(\mathrm{i}\psi_j)$, $\bar{n}_j$ and ψ_j represents the initial average photon number and the direction angle of the excitation for j $(j \equiv 1, 2)$ mode, respectively.

The field density operator for the system is given by

$$\rho_F(0) = \mid \psi_F(0)\rangle\langle\psi_F(0) \mid . \tag{10}$$

The reduced density of the atom can be expressed as

$$\rho_A(t) = \mathrm{Tr}_{\mathrm{field}}\{\rho(t)\} = \begin{bmatrix} \langle D|D\rangle & \langle T|D\rangle \\ \langle D|T\rangle & \langle T|T\rangle \end{bmatrix}, \tag{11}$$

where, when the atom is in a pure state,

$$\begin{aligned} \mid D\rangle = & \left(\frac{1}{\sqrt{1+S^2}}\right)\sum_{n_1,n_2=0}^{\infty} F(n_1)F(n_2)\Bigg\{\cos(g\theta(t)\gamma_{n_1+1,n_2+1}) \\ & - \mathrm{i}S\sqrt{\frac{\bar{n}_1\bar{n}_2}{(n_1+1)(n_2+1)}}\exp(-\mathrm{i}\beta)\sin(g\theta(t)\gamma_{n_1+1,n_2+1})\Bigg\} \mid n_1, n_2\rangle, \end{aligned} \tag{12}$$

$$\begin{aligned} \mid T\rangle = & \left(\frac{1}{\sqrt{1+S^2}}\right)\sum_{n_1,n_2=0}^{\infty} F(n_1)F(n_2)\Bigg\{S\exp(-\mathrm{i}\varphi)\cos(g\theta(t)\gamma_{n_1,n_2}) \\ & + (-\mathrm{i})\sqrt{\frac{(n_1+1)(n_2+1)}{\bar{n}_1\bar{n}_2}}\sin(g\theta(t)\gamma_{n_1,n_2})\Bigg\} \mid n_1, n_2\rangle, \end{aligned} \tag{13}$$

when the atom is in a mixed state,

$$\begin{aligned} \langle D|D\rangle &= \sum_{n_1,n_2=0}^{\infty} F(n_1)F(n_2)\left\{\eta_1\cos(g\theta(t)\gamma_{n_1,n_2})^2 + \eta_2\frac{\bar{n}_1\bar{n}_2}{(n_1+1)(n_2+1)}\sin(g\theta(t)\gamma_{n_1,n_2})^2\right\}, \\ \langle T|T\rangle &= 1 - \langle D|D\rangle, \\ \langle T|D\rangle &= \langle D|T\rangle = 0, \end{aligned} \tag{14}$$

where $\gamma_{n_1,n_2} = \sqrt{n_1, n_2}$, $\beta = \varphi - (\psi_1 + \psi_2)$ demonstrates the relative phase between the atom and the fields. We choose $\varphi = 0$ and $\beta = 0$ in the following calculation.

The eigenvalues of $\rho_A(t)$ can be written from Eq.(11)[22]

$$\lambda_A^{\pm} = \langle D|D\rangle \pm \exp(\mp\delta)|\langle D|T\rangle|, \tag{15}$$

where

$$\sinh(\delta) = \sinh^{-1}\left[\frac{1}{2\langle D|T\rangle}(\langle D|D\rangle - \langle T|T\rangle)\right]. \tag{16}$$

3. The definition of the optical entropy squeezing sudden generation

First, we introduce atomic optimal entropy squeezing (AOES). Using the reduced atomic density operator $\rho_A(t)$ given by Eq.(11), we can obtain[13]

$$\begin{aligned} H(S_x) = & -\left[\frac{1}{2} + \mathrm{Re}(\langle D|T\rangle)\right]\ln\left[\frac{1}{2} + \mathrm{Re}(\langle D|T\rangle)\right] \\ & -\left[\frac{1}{2} - \mathrm{Re}(\langle D|T\rangle)\right]\ln\left[\frac{1}{2} - \mathrm{Re}(\langle D|T\rangle)\right], \\ H(S_y) = & -\left[\frac{1}{2} + \mathrm{Im}(\langle D|T\rangle)\right]\ln\left[\frac{1}{2} + \mathrm{Im}(\langle D|T\rangle)\right] \\ & -\left[\frac{1}{2} - \mathrm{Im}(\langle D|T\rangle)\right]\ln\left[\frac{1}{2} - \mathrm{Im}(\langle D|T\rangle)\right], \\ H(S_z) = & -\langle T|T\rangle\ln\langle T|T\rangle - \langle D|D\rangle\ln\langle D|D\rangle, \end{aligned} \tag{17}$$

where, $H(S_\alpha)$ $(\alpha = x, y, z)$ are the information entropy of the Pauli operators S_α $(\alpha = x, y, z)$ for a

two-level atom system, $\langle D|D\rangle$, $\langle T|T\rangle$ and $\langle T|D\rangle$ are given by Eqs.(12), (13) and (14) when the initial atom is in the pure state and the mixed state, respectively.

The fluctuation of the atomic dipole component $S(\alpha)$ ($\alpha \equiv x$ or y), i.e. quantum noise, is said to be entropy squeezing if $H(S_\alpha)$ satisfies the following condition:[12]

$$E_\alpha = \delta H(S_\alpha) - \frac{2}{\sqrt{|\delta H(S_z)|}} < 0, \quad (\alpha \equiv x \text{ or } y). \tag{18}$$

where, $\delta H(S_\alpha) = \exp[H(S_\alpha)]$, E_α is entropy squeezing factor. The range of $H(S_\alpha)$ is $0 \sim \ln 2$, while that of $\delta H(S_\alpha)$ is $1\sim 2$. So, the AOES obtained as $E(S_\alpha) = 1 - \sqrt{2} \approx -0.414$, when quantum noise is minimum. In addition, if E_α takes value –0.414, which shows the generation of AOES in the component S_α.

Therefore we define: if the value of E_α falls suddenly from the maximum to the minimum –0.414 in the linear finite time, it is called the AOESSG in the component S_α.

Obviously, AOESSG may be applied widely in the quantum information process and the quantum computer because it can suppress the quantum noise in an instance.

In addition, the atom interacts with the field (its environment) inevitably, which will induce quantum entanglement between the atom and the field (QEAF), and QEAF can be measured by using the atomic reduced entropy S_a. We express the reduced entropy S_a in terms of the eigenvalues of $\rho_A(t)$ given by Eq.(16),[21,22]

$$S_a = -\lambda_A^\dagger \log_2 \lambda_A^\dagger - \lambda_A^- \log_2 \lambda_A^-. \tag{19}$$

If the value of S_a falls suddenly for maximum value 1 to minimum value 0 in the non-smooth finite time, we call it the entanglement sudden death between atom and the fields (ESDAF).

4. Numerical results and discussions

On the basis of the analytical solution presented in the previous section we now numerically examine the AOESSG and its control for the atom in a different initial state.

4.1. Relations between the AOESSG and ESDAF

First, we analyze the relation between the AOESSG and ESDAF.

The time evolution of the entropy squeezing factor E_x and the atomic reduced entropy S_a are plotted in Figs.1(a) and 1(b), respectively, for the initial case of the atom is in excited state with $S = 0$, atomic speed $v = gL/\pi$ and field-mode structure parameter $p = 1$; the field in the coherent state with the average photon number $\bar{n}_1 = \bar{n}_2 = 40$.

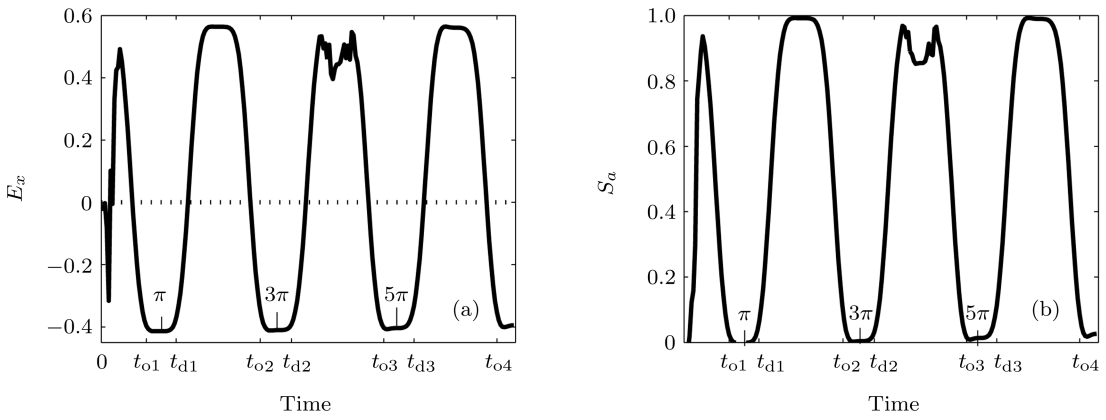


Fig.1. The time evolution of (a) E_x and (b) S_a. The atom initially in an excited state with $S = 0$, $v = gL/\pi$ and $p = 1$; the fields with $\bar{n}_1 = \bar{n}_2 = 40$.

It is clearly seen that

(i) E_x and S_a evolve periodically as an approximate wave with the period 2π.

(ii) According to Fig.1(a), first, at the time $T_{\rm O} = [2m+1]t_{\rm oi}$ ($i = 1, 2\ldots$, $t_{\rm o1} = 2.18$), E_x rapidly change

from maximum value to minimum value –0.414 in the linear finite time, namely the AOESSG at $T_{\rm O}$; second, in the time interval $\Delta T_{\rm OD} = T_{\rm D} - T_{\rm O}$, where $T_{\rm D} = [2m+1]t_{\rm d1}, t_{\rm d1} = 3.86, m = 0, 1, 2\ldots)$, the AOESSG was kept. Finally, the AOES suddenly disappeared at $T_{\rm D}$; here $T_{\rm O}, T_{\rm D}$ and $\Delta T_{\rm OD}$ are defined as the sudden generation, sudden disappearing time of the AOES, and duration of the AOESSG, respectively.

(iii) Figure 1(b) shows, in the initial stage $0 \sim t_{\rm o1}$ of the time, the S_a takes its maximum value 1, which is referred to as the maximum QEAF; but at just $T_{\rm O}$, the S_a can terminate abruptly in finite time, the ESDAF occurs according to our definition, and will remain in $\Delta T_{\rm OD}$. Moreover at $T_{\rm D}$ the QEAF reappears.

Physically, all these features can be quantitatively interpreted as follows: substituting the parameters in Fig.1 into Eqs.(12), (13), (15) and (16), and after a straightforward calculation, we can obtain $\lambda^{\dagger} \approx 1$ and $\lambda^{-} \approx 0$, so $S_a = 0$, at time $T_{\rm O}$ and in range $\Delta T_{\rm OD}$. That is the ESDAF, which leads to the atom achieved its pure state[12,22]

$$|\psi_A(T_{\rm O} \text{ or } \Delta T_{\rm OD})\rangle \simeq (|+\rangle + |-\rangle)/\sqrt{2}, \qquad (20)$$

which is the eigenstate of the atomic Pauli operator S_x. From Eqs.(11) and (18), we obtain information entropies of atomic Pauli operators S_x, and S_z at this time and they are, respectively, $H(S_x) = 0.0$, $H(S_z) = \ln 2$. Correspondingly, $\delta H(S_x) = 1$, $\delta H(S_z) = 2$. By using these results the entropy squeezing factor is calculated to be $E_x \simeq -0.414 < 0$. That shows the AOESSG in the operator S_x at $T_{\rm O}$, and the AOESSG which is kept in $\Delta T_{\rm OD}$. Clearly, at time $T_{\rm D}$, QEAF reappears, in a mixed state since the atom movess rapidly away from the eigenstate of S_x. That is why the AOES suddenly disappears at $T_{\rm D}$. So we find that the ESDAF leads to the AOESSG of the operator S_x, and the reappearance of QEAF causes AOES to be terminated abruptly.

4.2. Control of the AOESSG

An important prerequisite for the applicability of AOESSG is its controllability in the experiment. Here, we discuss the control parameter of the AOESSG by choosing the atomic initial state.

4.2.1. Control of duration of the AOESSG

First, let us consider the influence of the field-mode structure parameter p on the AOESSG. Figures 2(a)–2(c) present the time evolution of E_x for the atom initially in the excited state with $S = 0$, $v = gL/\pi$ and the field-mode structure parameter $p = 0.5$, $p = 1$ and $p = 2$, respectively. The fields in the coherent state with $\bar{n}_1 = \bar{n}_2 = 40$.

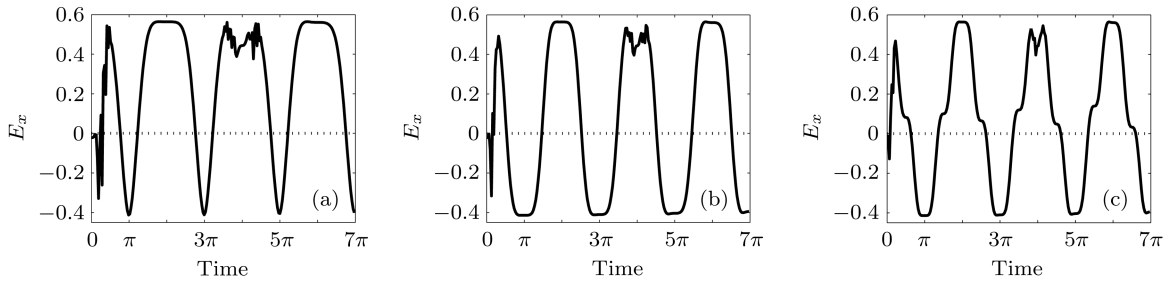


Fig.2. The time evolution of E_x for the field with $\bar{n}_1 = \bar{n}_2 = 40$, atom initially in an excited state with $S = 0$, speed $v = gL/\pi$ and (a) $p = 0.5$ (b) $p = 1$ (c) $p = 2$.

From these figures we can find: (i) When the field-mode structure parameter $p = 0.5$, just at time $T_{\rm O} = (2m+1)\pi$ $(m = 0, 1, 2\ \ldots)$ there is the AOESSG, but it cannot be kept (see Fig.2(a)), that is $\Delta T_{\rm OD}^{p=0.5} = 0$.

(ii) When $p = 1$, we can observe that not only the AOESSG occurs but also the AOESSG can be kept in $\Delta T_{\rm OD}^{p=1}$ (see Fig.2(b)).

(iii) Figure 2(c) shows, when $p = 2$, the AOES can be kept in $\Delta T_{\rm OD}^{p=2} > 0$ too, but generation of the AOES is a non-linear process, thus does not suddenly take place in our definition. Comparing Fig.2(b) with Figs.2(a) and 2(c), we find that $\Delta T_{\rm OD}^{p=1}$ is the longest duration of the AOESSG.

These features can be attributed in the atom-field interaction time due to atomic motion. The time fac-

tor $g\theta(t) = \dfrac{1}{2g}\left[gt - \dfrac{1}{2p}\sin(2pgt)\right]$ is made up of two parts: one is the linear part $1/2gt$, and the other is the nonlinear part $\dfrac{1}{4p}\sin(2pgt)$ whose amount is very small ($\leq 1/4p$), because $g\theta(t) \approx 1/2gt$ holds approximately. This leads to the period of the AOESSG to be 2π, but the nonlinear part determines the range of $\Delta T_{\rm OD}$. It is shown that the duration $\Delta T_{\rm OD}$ changes non-linearly with p. Hence, the duration $\Delta T_{\rm OD}$ of the AOESSG can be controlled by choosing the field-mode structure parameter p.

4.2.2. Control of component number of the AOESSG

In Figs.3. we have plotted the time evolution of the E_x and E_y for the fields with $\bar{n}_1 = \bar{n}_2 = 40$. In Figs.3(a) and 3(b), the atom stays initially in excited state ($S = 0$), while in Figs.3(c) and 3(d), the atom is initially in the coherent superposition state ($S = 1$).

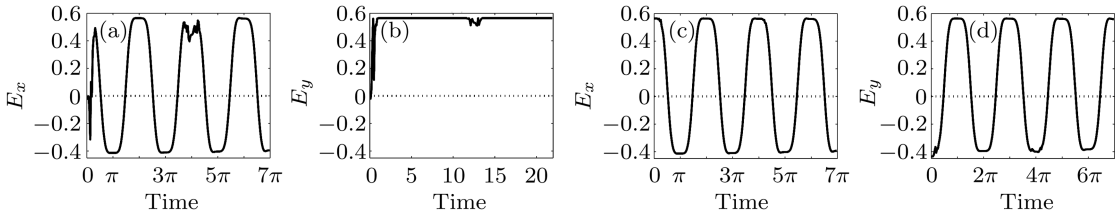


Fig.3. The time evolution of the squeezing factor for $\bar{n}_1 = \bar{n}_2 = 40$, $v = gL/\pi$ and $p = 1$. The case (i), atom initially in excited state with $S = 0$, (a) E_x and (b) E_y; the case (ii), atom initially in coherent superposition state with $S = 1$, (c) E_x and (d) E_y.

It is clear that if $S = 0$, the AOESSG merely occurs in component S_x, rather than S_y (see Figs.3(a) and 3(b)); when we choose the atom being initially in the coherent superposition state with $S = 1$, the AOESSG can occur in both components S_x and S_y at the different times alternatively (see Figs.3(c) and 3(d)). Therefore we can control the component number of the AOESSG by choosing atomic coherence.

4.2.3. Control of a stable cycle of the AOESSG

Finally, we study the stability of the AOESSG. Figures 4(a)–4(c) show the time evolution of E_x for the atom initially in the pure state ($S = 0$ or $S = 1$), the general mixed state with $\eta_1 = 0.1$, $\eta_2 = 0.9$ and the maximal mixed state with $\eta_1 = \eta_2 = 0.5$, respectively.

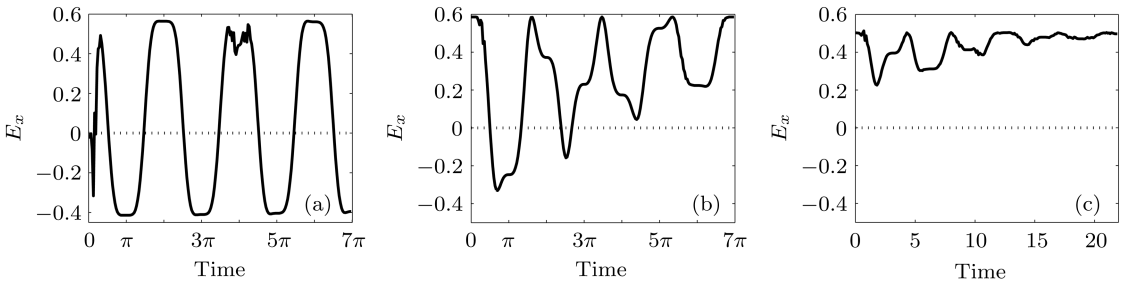


Fig.4. The time evolution of E_x with $v = gL/\pi$ and $p = 1$ for the atom initially in (a) the pure state ($S = 0$ or $S = 1$); (b) the general mixed state ($\eta_1 = 0.1, \eta_2 = 0.9$) and (c) the maximal mixed state ($\eta_1 = \eta_2 = 0.5$).

Obviously, when the atom is initially in the pure state, there is a stable cycle of the AOESSG, see Fig.4(a); in Fig.4(b), there is also an atomic entropy squeezing, but the AOESSG disappears, when the atom initially in the general mixed state; figure 4(c) shows that atomic entropy squeezing completely disappears, when the atom is initially in the maximal mixed state. So, the atomic mixed degree can seriously damage the AOESSG and is

one of the important reasons causing quantum noise. The results show that, in order to obtain a stable cycle of the AOESSG, we must choose the atom initially in the pure state ($S = 0$ or $S = 1$).

5. Conclusion

From the viewpoint of quantum information, for the system of an effective two-level moving atom which entangles with the two-mode coherent fields, we have proposed the concept and the definition of the AOESSG, researched the relationship between the AOESSG and the ESDAF, discussed the influences of the atomic initial state on the AOESSG and obtained the system parameters which control the AOESSG. Our conclusion is as follows: first, we find that the ESDAF leads to the occurrence of the AOESSG of the operator S_x and the reappearance of QEAF make AOESSG being terminated abruptly. Second, we can realize the transfer of the AOESSG in the component S_x and S_y by choosing atomic coherence. Third, the duration $\Delta T_{\rm OD}$ of the AOESSG can be controlled by choosing the field-mode structure parameter p. Finally, we can obtain a stable cycle of the AOESSG by choosing the atom initially in the pure state ($S = 0$ or $S = 1$). Our results are important for the experimental realization of the AOESSG and its application in quantum information process and quantum computer. Our studied model is a good system of the AOESSG. However, since a three-level atom in the λ, Ξ and $\wedge$-type configurations respectively with arbitrary detuning can be exactly reduced to a two-level system,[23−25] whose effective Hamiltonian is given by Eq.(1), then our results can also be suitable for the entropy squeezing question of a three-level system.

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