Effects of inhomogeneous couplings between atoms and a cavity field on entanglement dynamics*

Guo Jin-Liang(郭金良)†, Xia Yan(夏 岩), and Song He-Shan(宋鹤山)

School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, *China*

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Based on the concept of concurrence, we have investigated the entanglement dynamics of two two-level atoms coupled to a single-mode cavity field with inhomogeneous couplings. We find that, for some initial states, the inhomogeneous couplings not only induce but also enhance the entanglement in the process of its evolution. In addition, considering the intrinsic decoherence proposed by Milburn, we also find that a proper value of inhomogeneous couplings can enhance the stationary entanglement, and as a result, the destructive effect of intrinsic decoherence on entanglement can be moderated by the inhomogeneous couplings.

Keywords: entanglement evolution, intrinsic decoherence

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1. Introduction

Entanglement is one of the most striking features of quantum mechanical systems that have no classical analog. It has been the focus of much work recently due to its key role in the topical area of quantum information processing.[1−3] Over the past few years, there has been considerable interest in preparing entanglement among separate particles based on optical systems,[4] cavity-quantum electrodynamics (QED),[5] ion traps[6] and Heisenberg interaction systems.[7−9] In particular, recent advance in ion trapping technology[10] and cavity QED[11] provides suitable scenarios for manipulating quantum systems; as a result, much attention has been directed to the generation of entangled states in cavity-QED and two-atom and multi-particle entanglements have been demonstrated in cavity QED.[12]

Most of the previous studies are based on an essential assumption that the coupling strengths of the two atoms to the cavity mode are equal, which is a good approximation for atoms in a microwave cavity. However, in an optical cavity, the coupling strengths between the atoms and the cavity depend on the location of the atoms in the cavity field, and the two atoms usually no longer possess equivalent coupling strengths to the cavity field. Therefore, a deep understanding of the effects of inhomogeneous couplings between the atoms and the cavity field on entanglement creation is desirable. Quite recently, Natali and Ficek[13] found that spatial variation of the coupling constants actually helps to create transient entanglement, and when the initial atomic state is entangled, the entanglement will remain all the time. Motivated by this, in this paper we will investigate the effects of inhomogeneous couplings on entanglement dynamics between the atoms. In addition, considering the decoherence process, we also take the intrinsic decoherence proposed by Milburn[14] into account. The system discussed here consists of two identical two-level atoms coupled to a single-mode field. The ground and excited states of atoms are denoted by $|g\rangle_i$ and $|e\rangle_i$ $(i = 1, 2)$ respectively. Under the rotating-wave approximation, the Hamiltonian for this model is[15]

$$H = \omega a^\dagger a + \frac{\omega_0}{2}(\sigma_z^1 + \sigma_z^2) + \lambda_1(a^\dagger \sigma_-^1 + a\sigma_+^1) + \lambda_2(a^\dagger \sigma_-^2 + a\sigma_+^2), \quad (1)$$

where a and $a^\dagger$ are respectively the annihilation and creation operators of the single-mode cavity field with frequency ω; σ_z and $\sigma_\pm$ are the atomic inversion and transition operators, and ω_0 is the atomic transition frequency of the atoms. λ_1 and λ_2 are the coupling constants of the cavity field and atom 1 with atom 2, respectively.

To quantify the amount of entanglement associated with a given two-qubit state ρ, we consider the concurrence defined by Wootters[16]

$$C = \max\{\lambda_1 - \lambda_2 - \lambda_3 - \lambda_4, 0\}, \quad (2)$$

where the quantities $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \lambda_4$ are the square roots of the eigenvalues of the matrix $\boldsymbol{R} =$

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†Corresponding author. E-mail: guojinliang80@163.com

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$\rho(\sigma_y \otimes \sigma_y)\rho^*(\sigma_y \otimes \sigma_y)$. ρ^* denotes the complex conjugate of ρ and σ_y is the normal Pauli operator. The concurrence $C = 0$ corresponds to an unentangled state and $C = 1$ for a maximally entangled state. For the special case

$$\boldsymbol{\rho} = \begin{pmatrix} a & 0 & 0 & w \\ 0 & b & y & 0 \\ 0 & y & c & 0 \\ w^* & 0 & 0 & d \end{pmatrix}, \tag{3}$$

the concurrence can be easily obtained

$$C = 2\max\{0, |y| - \sqrt{ad}, |w| - \sqrt{bc}\}. \tag{4}$$

This paper is organized as follows: In Section 2, we study the effects of inhomogeneous couplings between the atoms and cavity field on the entanglement evolution for different initial states. In Section 3, taking intrinsic decoherence into account, we put emphasis on the enhancement of stationary entanglement by controlling the inhomogeneous couplings. Finally we conclude in Section 4.

2. Entanglement evolution between the two atoms

First, we assume that the two atoms are initially in a partially entangled atomic state, that is a combination of the Bell states $|\Psi_{12}\rangle = \cos\alpha|eg\rangle + \sin\alpha|ge\rangle$, and the cavity field is in vacuum state $|0\rangle$. Then the initial state for the total system is given by

$$|\Psi(0)\rangle = \cos\alpha|eg0\rangle + \sin\alpha|ge0\rangle. \tag{5}$$

The solution of the system in terms of a standard basis can be written as

$$|\Psi(t)\rangle = x_1|eg0\rangle + x_2|ge0\rangle + x_3|gg1\rangle, \tag{6}$$

where the corresponding coefficients are

$$\begin{aligned} x_1(t) &= \frac{\lambda_1}{\lambda^2}(\lambda_1\cos\alpha + \lambda_2\sin\alpha)\cos(\lambda t) \\ &\quad -\frac{\lambda_2}{\lambda^2}(\lambda_1\sin\alpha - \lambda_2\cos\alpha), \\ x_2(t) &= \frac{\lambda_2}{\lambda^2}(\lambda_1\cos\alpha + \lambda_2\sin\alpha)\cos(\lambda t) \\ &\quad +\frac{\lambda_1}{\lambda^2}(\lambda_1\sin\alpha - \lambda_2\cos\alpha), \end{aligned}$$

$$x_3(t) = -\frac{\mathrm{i}}{\lambda}(\lambda_1\cos\alpha + \lambda_2\sin\alpha)\sin(\lambda t) \tag{7}$$

with $\lambda = \sqrt{\lambda_1^2 + \lambda_2^2}$. Here the cavity mode is assumed to be resonant with the atomic transition frequency, i.e., $\omega_0 = \omega$. The information about the entanglement between the two atoms is contained in the reduced density matrix which can be obtained by tracing out the cavity field. Then from Eq. (4) we obtain the concurrence $C_{12} = 2|x_1x_2^*|$. For the case of unentangled initial state, i.e., $\alpha = 0$ or $\alpha = \pi/2$, C_{12} can be written as

$$C_{12} = \frac{2\lambda_1\lambda_2}{\lambda^4}|(\lambda_1^2\cos(\lambda t) + \lambda_2^2)(1 - \cos(\lambda t))|, \tag{8}$$

and when the coupling strengths of the atoms to the cavity field are equal, namely, $\lambda_1 = \lambda_2$, we obtain $C_{12} = (1/2)\sin^2\theta$ with $\theta = \sqrt{2}\lambda_1 t$. Then one can see that the entanglement oscillates with time t periodically and the maximal value that the entanglement can reach is 1/2. But when $\lambda_1 \neq \lambda_2$, for example, $\lambda_2 = 2\lambda_1$, C_{12} reduces to

$$C_{12} = \frac{4}{25}|(\cos\varphi + 4)(\cos\varphi - 1)| \tag{9}$$

with $\varphi = \sqrt{5}\lambda_1 t$, and the maximum of C_{12} increases to $24/25 \sim 1$, which also can be seen from Fig. 1. In Fig. 1 the time evolution of concurrence C_{12} for different initial states is plotted. One can conclude that the entanglement may be enhanced to a great extent by using the inhomogeneous couplings when the initial atomic state is unentangled. As for $\alpha = \pi/3$ and $\pi/12$, i.e, initially the atomic states are entangled, we find that a second maximum of entanglement appears after the major maximum when $\lambda_1 = \lambda_2$. Introducing $\lambda_2 = 2\lambda_1$, we see that the second maximum of entanglement is enhanced, which exceeds the initial entanglement for $\alpha = \pi/12$, and the entanglement can nearly remain a steady value in some regions of time. This result is very interesting since it implies that the inhomogeneous couplings may be a possible way to enhance the entanglement in the entanglement evolution. However, here we still point out that the entanglement evolution is dependent on the initial states and the difference between λ_1 and λ_2, that is to say, not all cases support our conclusion. For example, when $\alpha = \pi/4$, i.e, initially the atomic state is the maximally entangled state, in contrast with the case $\lambda_1 = \lambda_2$, the entanglement will decrease in some time intervals when introducing $\lambda_2 = 2\lambda_1$.

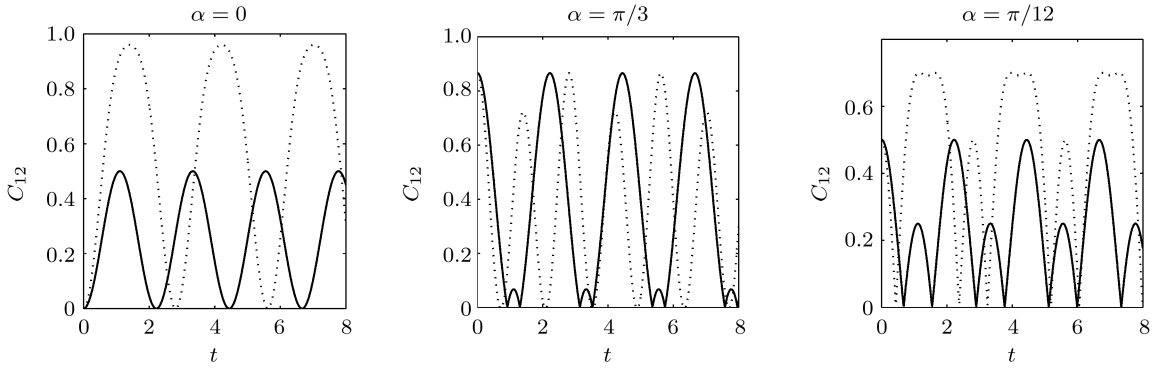


Fig. 1. The concurrence C_{12} as a function of time t for different values of superposition parameter α when the atoms are initially in the state $\cos\alpha|eg\rangle + \sin\alpha|ge\rangle$. The parameters are $\lambda_1 = \lambda_2 = 1$ (solid line), $\lambda_1 = \frac{1}{2}\lambda_2 = 1$ (dotted line).

Next we choose a combination of other Bell states as the initial atomic state $|\Psi_{12}\rangle = \cos\alpha|ee\rangle + \sin\alpha|gg\rangle$, and the cavity field is also in vacuum state $|0\rangle$. Then the initial state for the total system is given by

$$|\Phi(0)\rangle = \cos\alpha|ee0\rangle + \sin\alpha|gg0\rangle, \tag{10}$$

in which the state of the total system at time t can be expressed in the standard basis

$$\begin{aligned}|\Phi(t)\rangle \;=\; & x_1|ee0\rangle + x_2|gg0\rangle + x_3|ge1\rangle \\ & + x_4|eg1\rangle + x_5|gg2\rangle.\end{aligned} \tag{11}$$

Substituting the state $|\Phi(t)\rangle$ into the Schrödinger equation ($\hbar = 1$), under the resonance conditions, one can obtain the equations of amplitudes x_i (i = 1–5) as

$$\begin{aligned}\mathrm{i}\dot{x_1} &= \omega x_1 + \lambda_1 x_3 + \lambda_2 x_4, \\ \mathrm{i}\dot{x_2} &= -x_2\omega, \\ \mathrm{i}\dot{x_3} &= \lambda_1 x_1 + \omega x_3 + \sqrt{2}\lambda_2 x_5, \\ \mathrm{i}\dot{x_4} &= \lambda_2 x_1 + \omega x_4 + \sqrt{2}\lambda_1 x_5, \\ \mathrm{i}\dot{x_5} &= \sqrt{2}\lambda_2 x_3 + \sqrt{2}\lambda_1 x_4 + \omega x_5.\end{aligned} \tag{12}$$

Since the solutions of Eq. (12) are very complicated, here skipping the details we give the result in terms of figures. From Eq. (4), tracing out the cavity field, we obtain

$$\begin{aligned}C \;=\; & 2\max\big\{0, |x_1 x_2^*| - |x_3 x_4^*|, |x_3 x_4^*| \\ & - |x_1|\sqrt{(|x_2|^2 + |x_5|^2)}\big\}.\end{aligned} \tag{13}$$

In Fig. 2, we plot the concurrence C_{12} as a function of time t when the initial state is assumed to be expressed by Eq. (10). For $\alpha = 0$, compared to the result for the initial state (5), we find there is no entanglement all the time when $\lambda_1 = \lambda_2$, but we can induce entanglement by introducing the inhomogeneous couplings. In addition, one point deserving mention

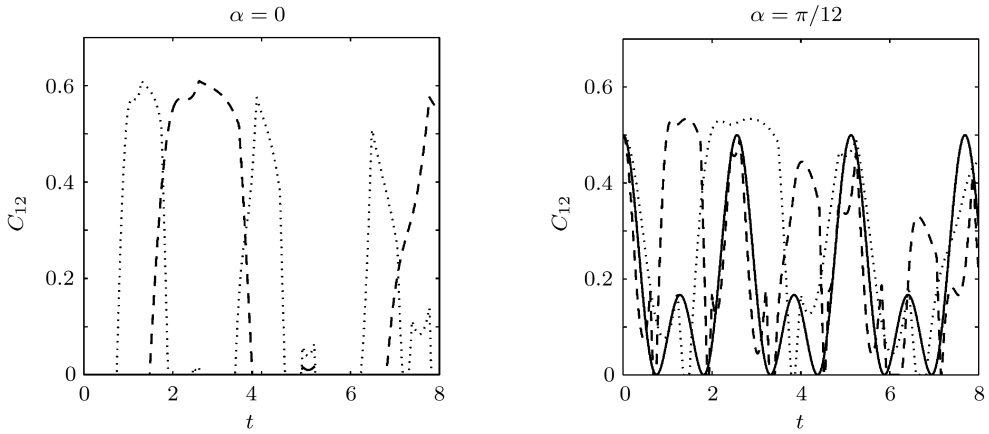


Fig. 2. The concurrence C_{12} as a function of time t for different values of superposition parameter α when the atoms are initially in the state $\cos\alpha|ee\rangle + \sin\alpha|gg\rangle$. The parameters are $\lambda_1 = \lambda_2 = 1$ (solid line), $\lambda_1 = 1,\ \lambda_2 = 2$ (dotted line), $\lambda_1 = 1,\ \lambda_2 = 1/2$ (dashed line).

here is that the phenomena of entanglement sudden death[17−20] and sudden birth[21] appear in the process of entanglement evolution. In other words, the entanglement does not always exist, but at some time the entanglement falls abruptly to zero and there is a threshold value of time t, only above which concurrence begins to be nonzero. Furthermore, the death and birth durations are sensitive to the inhomogeneous couplings. For example, both durations are shorter for the case $\lambda_1 = 1, \lambda_2 = 2$ than those in the case $\lambda_1 = 1, \lambda_2 = 1/2$. When the initial atomic state is entangled, such as at $\alpha = \pi/12$, similar to the result for the initial state (5), we find that the entanglement is enhanced by the inhomogeneous couplings, but the difference is that the entanglement is affected by the effect of entanglement sudden death, though this effect is very weak.

3. Enhancement of stationary entanglement by inhomogeneous couplings

It is well known that from the practical point of view, the real quantum systems will unavoidably interact with the surrounding environment, thus leading to decoherence. In recent years, ongoing efforts have been applied to solve the problem of decoherence. One approach is to modify the Schrödinger equation in such a way that the quantum coherence is automatically destroyed as the quantum system evolves. This effect is called intrinsic decoherence, proposed by Milburn.[14] Based on the assumption that in sufficiently short time steps the system does not evolve continuously under unitary evolution but rather in a stochastic sequence of identical unitary transformations, the master equation describing the intrinsic decoherence under the Markovian approximations is given by

$$\frac{\mathrm{d}\rho(t)}{\mathrm{d}t} = -\mathrm{i}[H,\rho] - \frac{\gamma}{2}[H,[H,\rho(t)]], \tag{14}$$

where γ is the intrinsic decoherence rate. The formal solution of the above master equation can be expressed as[22]

$$\rho(t) = \sum_{k=0}^{\infty} \frac{(\gamma t)^k}{k!} M^k(t)\rho(0)M^{\dagger k}(t), \tag{15}$$

where $\rho(0)$ is the density operator of the initial system, and $M^k(t)$ is defined by

$$M^k(t) = H^k \exp(-\mathrm{i}Ht) \exp\left(-\frac{\gamma t}{2}H^2\right). \tag{16}$$

Recently, effects of intrinsic decoherence on the entanglement in atom–field systems[23,24] and various Heisenberg models[25−28] have been discussed, since the presence of intrinsic decoherence leads to a diagonalization of the density matrix in the energy eigenvectors basis. If some, or all, eigenvectors are entangled, then for some initial states, even in the limit of $t \to \infty$, a stationary entanglement can be found in the system. The generation of steady state entanglement between atoms in a cavity has been investigated with more physically motivated decoherence models in different papers. Schneider and Milburn[29] investigated the model given in Eq. (1) for $\lambda_1 = \lambda_2$ with the addition of cavity decay. In Ref. [13], spontaneous emission and inhomogeneous couplings have also been taken into consideration. Attempts to improve entanglement via feedback by using the model in this manuscript with homogeneous coupling and experimentally relevant decoherence sources have been published in the second paper of Ref. [5] and also in Ref. [30]. Therefore, in the following we are concerned with the stationary entangled state occurring in the entanglement evolution between the two atoms when the intrinsic decoherence is taken into account.

It is easy to examine that there exists a conserved quantity

$$K = a^{\dagger}a + 1 + \frac{\sigma_{1z} + \sigma_{2z}}{2}, \tag{17}$$

for the resonance case, i.e, $\omega_0 = \omega$. Then the eigenvalues of Hamiltonian (1) in the subspace $K = 1$ can be written as

$$E_1 = 0, \quad E_2 = \lambda, \quad E_3 = -\lambda, \tag{18}$$

and the corresponding eigenvectors are

$$\begin{aligned} |\Psi_1\rangle &= \frac{1}{\lambda}(\lambda_1|ge0\rangle - \lambda_2|eg0\rangle), \\ |\Psi_2\rangle &= \frac{\sqrt{2}}{2}\left(\frac{\lambda_1}{\lambda}|eg0\rangle + \frac{\lambda_2}{\lambda}|ge0\rangle + |gg1\rangle\right), \\ |\Psi_2\rangle &= \frac{\sqrt{2}}{2}\left(\frac{\lambda_1}{\lambda}|eg0\rangle + \frac{\lambda_2}{\lambda}|ge0\rangle - |gg1\rangle\right), \end{aligned} \tag{19}$$

where $\lambda = \sqrt{\lambda_1^2 + \lambda_2^2}$. Next, we choose the system initially in an entangled state $\rho(0) = |\Psi(0)\rangle\langle\Psi(0)|$, and

$$\Psi(0) = \cos\alpha|eg0\rangle + \sin\alpha|ge0\rangle. \tag{20}$$

Substituting the complete relation $\sum |\Psi_n\rangle\langle\Psi_n|\rho(t) \times|\Psi_m\rangle\langle\Psi_m|$ into Eq. (15), one can write the explicit expression of the density matrix as

$$\begin{aligned}\rho(t) &= \sum_{mn}\exp\left[-\frac{\gamma t}{2}(E_m-E_n)^2-\mathrm{i}(E_m-E_n)t\right]\langle\Psi_m|\rho(0)|\Psi_n\rangle|\Psi_m\rangle\langle\Psi_n| \\ &= \frac{1}{\lambda^2}(\lambda_1\sin\alpha-\lambda_2\cos\alpha)^2|\Psi_1\rangle\langle\Psi_1|+\frac{1}{2\lambda^2}(\lambda_1\cos\alpha+\lambda_2\sin\alpha)^2(|\Psi_2\rangle\langle\Psi_2|+|\Psi_3\rangle\langle\Psi_3|) \\ &+ \frac{\sqrt{2}}{2\lambda^2}\,\mathrm{e}^{-\frac{\gamma t}{2}\lambda^2}\left[\frac{1}{2}(\lambda_1^2-\lambda_2^2)\sin(2\alpha)-\lambda_1\lambda_2\cos(2\alpha)\right](\,\mathrm{e}^{\mathrm{i}t\lambda}|\Psi_1\rangle\langle\Psi_2|+\,\mathrm{e}^{-\mathrm{i}t\lambda}|\Psi_1\rangle\langle\Psi_3|+\mathrm{h.c}) \\ &+ \frac{1}{2\lambda^2}(\lambda_1\cos\alpha+\lambda_2\sin\alpha)^2\,\mathrm{e}^{-2\lambda^2\gamma t}(\,\mathrm{e}^{-2\mathrm{i}\lambda t}|\Psi_2\rangle\langle\Psi_3|+\mathrm{h.c}),\end{aligned} \tag{21}$$

where $E_{m,n}$ and $\Psi_{m,n}$ are the eigenvalues and the corresponding eigenvectors of H in the subspace $K=1$ respectively. By tracing out the degree of the cavity field, we obtain the analytical expression of the reduced density matrix for the two atoms as follows:

$$\rho_{12}(t) = \mu|gg\rangle\langle gg|++\nu|eg\rangle\langle eg|+\chi|ge\rangle\langle ge|+\delta|eg\rangle\langle ge|+\delta^*|ge\rangle\langle eg|, \tag{22}$$

and the concurrence is $C_{12}=2|\delta|$, where

$$\begin{aligned}\delta &= -\frac{\lambda_1\lambda_2}{\lambda^4}(\lambda_1\sin\alpha-\lambda_2\cos\alpha)^2+\frac{\lambda_1\lambda_2}{2\lambda^4}(\lambda_1\cos\alpha+\lambda_2\sin\alpha)^2 \\ &+\frac{1}{\lambda^4}\,\mathrm{e}^{-\frac{\gamma t}{2}\lambda^2}\cos(2\lambda t)\left[\frac{1}{2}(\lambda_1^2-\lambda_2^2)\sin(2\alpha)-\lambda_1\lambda_2\cos(2\alpha)\right](\lambda_1^2-\lambda_2^2) \\ &+ \frac{\lambda_1\lambda_2}{2\lambda^4}(\lambda_1\cos\alpha+\lambda_2\sin\alpha)^2\,\mathrm{e}^{-2\lambda^2\gamma t}\cos(2\lambda t).\end{aligned} \tag{23}$$

In Fig. 3 we plot the concurrence C_{12} as a function of time t for different initial states with equal coupling strengths of the atoms to the cavity field.

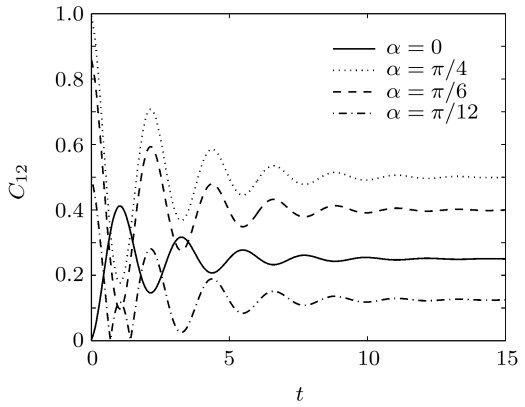


Fig. 3. The concurrence C_{12} as a function of time t for different values of superposition parameter α when the atoms are initially in the state $\cos\alpha|eg\rangle+\sin\alpha|ge\rangle$. The parameters are $\lambda_1=\lambda_2=1$, $\gamma=0.1$.

We find that the concurrence first oscillates with time and finally becomes a stationary value when the intrinsic decoherence is considered, which is in sharp contrast to the case without the intrinsic decoherence that the concurrence only oscillates with time periodically. This implies that the intrinsic decoherence does not completely destroy the entanglement, but drives the atoms into a stationary entangled state. Therefore, we confine our consideration to the question whether the stationary state is entangled or not and how to enhance the stationary entanglement. In the limit of $t\to\infty$, the concurrence C_{12} can be expressed as

$$\begin{aligned}C_{12}(t\to\infty) = \frac{\lambda_1\lambda_2}{\lambda^4}|&(\lambda_1\cos\alpha+\lambda_2\sin\alpha)^2 \\ &-2(\lambda_1\sin\alpha-\lambda_2\cos\alpha)^2|.\end{aligned} \tag{24}$$

It is easy to see that whether the stationary state is entangled or not is dependent on the coupling constants λ_1 and λ_2 and the initial state we choose. In the following, for simplicity, we assume the ration coefficient $\Omega=\lambda_2/\lambda_1$. For $\alpha=0$, the initial state reduces to the separate state $|eg0\rangle$, and the concurrence C_{12} turns out to be

$$C_{12}(t\to\infty)=\frac{\Omega}{(1+\Omega^2)^2}|1-2\Omega^2|, \tag{25}$$

when the time t approaches infinity. One can see that the stationary state is unentangled when the condition $\Omega=\sqrt{2}/2$ is satisfied in this case. When $\alpha=\pi/4$, the two atoms are initially prepared in the maximally entangled state $\frac{1}{\sqrt{2}}(|eg\rangle+|ge\rangle)$, then in the limit of $t\to\infty$, we have

$$C_{12}(t\to\infty)=\frac{\Omega}{2(1+\Omega^2)^2}|\Omega^2-6\Omega+1|. \tag{26}$$

That is to say, when $\Omega = 3 \pm 2\sqrt{2}$ the stationary entanglement disappears. In Fig. 4, the stationary entanglement as a function of ration coefficient Ω for different initial states is plotted. It is shown that for different regions of Ω there are obviously different effects on the stationary entanglement. For $\alpha = 0$ and $\pi/4$, the value of stationary entanglement increases from zero to a peak value and then decreases to zero again as the increase of the Ω, but on further increasing Ω, one can see that the maximum entanglements $C_{12}(\alpha = 0) = 0.56$ and $C_{12}(\alpha = \pi/4) = 0.5$ appear at $\Omega = 2$ and 1 respectively. For $\alpha = \pi/6$ and $\pi/12$, the stationary entanglement increases from zero to the maximal value 0.46 and 0.35 at $\Omega = 3/4$ and $1/2$ respectively; but after the death of stationary entanglement, it will recover gradually as Ω grows. Therefore, the ration coefficient Ω can efficiently control the stationary entanglement, and as a result, we may create or remove the stationary entangled state by virtue of Ω. However, compared to the case of equal coupling strengths of the atom to the cavity field, i.e, $\Omega = 1$, the value of stationary entanglement can be enhanced when introducing the ration coefficient Ω to some initial states, such as $\alpha = 0, \pi/6, \pi/12$. This means that a proper value of Ω can effectively weaken the destructive effect of the intrinsic decoherence on the entanglement, which may be very useful for the quantum information process.

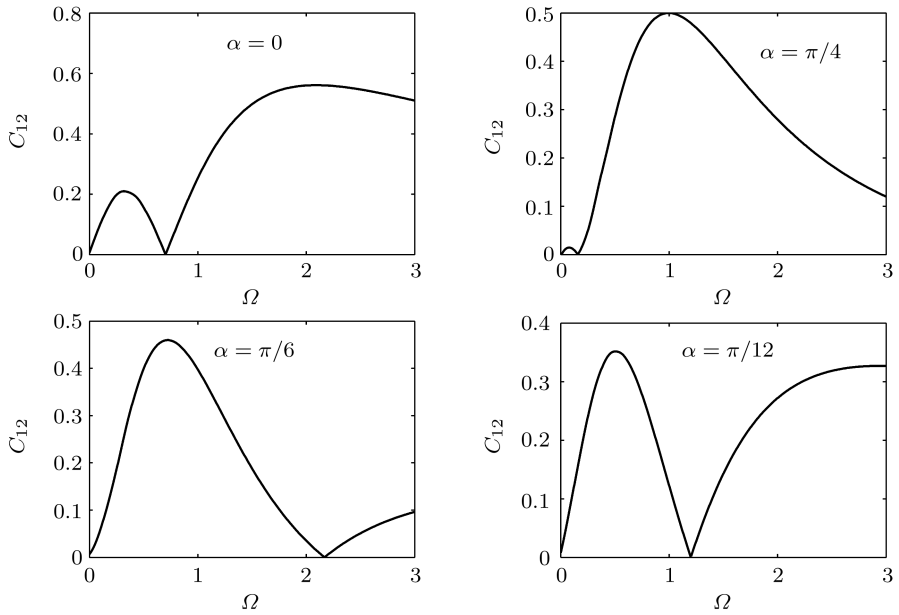


Fig. 4. The stationary entanglement as a function of ration coefficient $\Omega = \lambda_2/\lambda_1$ for different initial states. The parameter is $\gamma = 0.1$.

4. Conclusion

In conclusion, we have investigated the character of entanglement evolution between two two-level atoms coupled to a single-mode cavity field. Unlike the previous studies, the coupling strengths of the atoms to the cavity field are not equal to each other but inhomogeneous. Our results show that, compared to the case of equal couplings, a proper value of inhomogeneous couplings can enhance the entanglement for some initial states. Especially for the initial state $\cos\alpha|ee0\rangle + \sin\alpha|gg0\rangle$, the entanglement can be induced when introducing the inhomogeneous couplings, though the phenomenon of entanglement sudden death and sudden birth appears in the process of entanglement evolution. In addition, when the intrinsic decoherence is considered, we find the inhomogeneous couplings can effectively weaken the destructive effect of the intrinsic decoherence on the entanglement, therefore a proper value of inhomogeneous couplings can create and enhance the stationary entanglement.

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