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有心结构耦合腔系统中的几何量子失谐

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摘 要:引入了由 $N+1$ 个单模腔构成的有心结构耦合腔物理模型.其中,中心腔起耦合器作用,其余 N 个腔通过 N 条光纤与中心腔耦合,并且每个腔囚禁 1 个二能级原子.在系统激发数等于 1 的情况下,给出了系统态矢的演化规律,研究了两原子间和两腔场间的几何量子失谐.通过数值计算,讨论了耦合腔数目和原子与腔场间耦合强度对几何量子失谐的影响.研究结果表明:随着腔数目的增加两原子间和两腔场间的几何量子失谐都减弱;随着原子与腔场间耦合系数增大,两原子间几何量子失谐减弱,但两腔场间几何量子失谐却加强.

关键词:量子光学;有心结构耦合腔;几何量子失谐;量子关联
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Geometrical Quantum Discord in a Coupled Cavities System with a Center

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Abstract: A coupled-cavity system with a center is introduced. It is composed of $N+1$ single-mode cavities, each containing an identical two-level atom. One of them is at the center of the structure and is connected with other N cavities by optical fibers. The situation is considered that atom resonantly interacts with cavity field via a one-photon hopping, and the total excitation number of the system equals one. The evolution of the state vector of the system is derived. The geometrical quantum discords between atoms and that between cavities are investigated. The influences of atom-cavity coupling coefficient and the number of couple cavities on the geometrical quantum discords between two subsystems are studied. The results obtained by the numerical method show: the geometrical quantum discords between atoms and that between cavities are weakened with the increase of the number of coupled cavities; the atom-atom geometrical quantum discords is weakened, and the cavity-cavity geometrical quantum discords is strengthened with the increase of atom-cavity coupling constant.

Key words: Quantum optics; Coupled-cavity model with a center; Geometrical quantum discord; Quantum correction
OCIS Codes: 270.0270; 270.5580; 020.0020; 020.5580

0 Introduction

Quantum Discord (QD) is a useful indicator to measure quantum correlations in the composite bipartite system, which has been initially introduced by OLLIVIER H and ZUREK W H[1]. Now it has been found that QD captures more quantum correlations and is more widespread than the entanglement.

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Especially in some quantum systems whose entanglement is zero, but QD is present. Due to its critical role in quantum information processing, QD has attracted huge attention. In recent years, QD was investigated quite intensively[2-9]. For example, AIOBI H et al studied quantum entanglement and QD of a pair of two-level atoms with no direct interaction in the presence of a dissipative environment[2]. WANG Bo et al investigated the dynamics of quantum discord using an exactly solvable model where each qubit independently interacts with its own zero-temperature reservoir[3]. YI Xue-xi et al discussed the discord of a bipartite two-level system coupling to an XY spin-chain environment in a transverse field[4]. Unfortunately, the evaluation of QD requires a potentially complex optimization procedure in general and analytical results can be obtained only in a few restricted case. In order to avoid the optimization procedure of QD, DAKIC B et al put forward a new measure of quantum correlations for a more general bipartite quantum system, namely Geometric Quantum Discord (GQD)[10]. Its advantage is that it is able to give its analytical expression easily. So far, some new research progresses have been made for the GQD in different quantum systems[11-16]. For example, in Ref.[11] the GQD for a class of two-qubit non-X states is investigated. CHEN Hong et al discussed the level surfaces of GQD under some typical kinds of decoherence channels for a class non-X-structured state[12].

Cavity Quantum Electrodynamics (CQED), which concerns the interaction between photons and atoms within highly reflective cavities, provides an ideal physical implementation flat roofs for distributed quantum information processing. In the experiment, two atoms have been successfully prepared in an entangled state of the Einstein-Podolsky-Rosen, and a quantum phase gate operating on quantum bits has been realized by CQED technology, and so on[17-19]. In order to achieve distributed quantum computation, in 1997 PELLIZZARI T firstly introduced the coupled-cavity model and proposed a scheme for reliable transfer of quantum information between two atoms[20]. Because the coupled-cavity model can avoid the difficulty of manipulating multiple atoms in a single cavity, it has attracted much attention. In recently years, researchers have studied the possibility of quantum information processing realized via coupled-cavity systems[21-27]. For example, OGDEN C D et al discussed the dynamics of a system consisting of two cavities[21]. ZHANG Ye-qi et al proposed a scheme of entanglement transfer through arrays of cavities coupled by optical fibers[22]. HUANG Xiao-bin et al put forward an efficient scheme to generate three-atom W states in coupled cavities via transitionless quantum driving[23]. With the development of the CQED technique and the deepening of research, researchers have extended two coupled cavities to multiple coupled cavities, even to two-dimensional coupled cavities and coupled cavities networks[28-32]. For example, HUANG Xiao-bin et al analyzed the dynamics of a two-dimensional coupled cavity system under one-excitation condition[28]. The coherent transport behavior of a single-photon in T-type coupled cavity arrays has been investigated[30]. Motivated by previous researches, we have extended the T-type coupled-cavity model to a new coupled-cavity model with a center. The dynamics of GQD under one-excitation condition is discussed. Because the coupled-cavity system with a center has a higher symmetry than T-type coupled-cavity systems, it may have important applications in quantum information processing and quantum computation. Based on this system, we have proposed a one-step method to realize an n-qubit controlled phase gate with one cat-state qubit simultaneously controlling n-1 target cat-state qubits, and one of its advantages is that the gate operation time is independent of the number of the cat-state qubits[33]. We hope that this work has some reference values for quantum information processing.

1 The model

The coupled-cavity model with a center is shown in Fig.1. It consists of $N+1$ single-mode cavities, each containing a two level atom. Cavity 1 is placed at the center of the system and coupled with other N cavities via N fibers. We consider the situation that each atom resonantly interacts with the cavity field via a one-photon hopping. Under the short fiber limit and applying the rotating wave approximation, the Hamiltonian of the whole system in the interaction picture can be written as (setting $\hbar=1$)[20]

$$H_1=\sum_{j=1}^{N+1}g_j a_j s_j^{+}+\sum_{i=1}^{N}J_i b_i(a_{i+1}^{+}+a_1^{+})+\mathrm{H.C} \tag{1}$$

where $a_j^{+}(a_j)$ $(j=1,2,\cdots,N,N+1)$ stand for creation (annihilation) operator for the mode of cavity j,

b_i is the annihilation operator for the ith fiber mode, $s_j^+ = |e\rangle_{jj}\langle g|$ $(j=1,2,\cdots,N,N+1)$ is the raising operator of the jth atom between its ground state $|g\rangle_j$ and excited state $|e\rangle_j$, g_j is the atom-cavity coupling constant, J_j $(j=1,2,\cdots,N)$ denotes the cavity-fiber coupling constant, $H.C$ stands for the conjugate terms. For the sake of simplicity, we take $g_1=g_2=\cdots=g_{N+1}=g$ and $J_1=J_2=\cdots=J_N=J$.

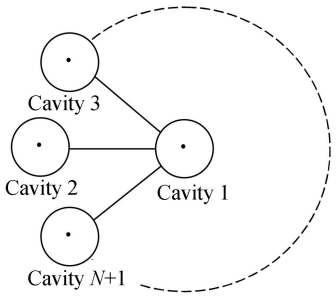


Fig.1 Sketch of the set-up

Initially, we consider that all cavities and fibers are in the vacuum state, atom 1 is prepared in anexcited state, and the other atoms are in the ground states. Thus, the combined initial state is $|\varphi_{a1}\rangle$, and the whole system evolves in the one-excitation subspace spanned by the basis state vectors

$$\begin{cases} |\varphi_{ai}\rangle = |e_i\rangle_a |0\rangle_c |0\rangle_f & i=1,2,\cdots,N,N+1 \\ |\varphi_{ci}\rangle = |g\rangle_a |1_i\rangle_c |0\rangle_f & i=1,2,\cdots,N,N+1 \\ |\varphi_{fl}\rangle = |g\rangle_a |0\rangle_c |1_l\rangle_f & l=1,2,\cdots,N \end{cases} \tag{2}$$

where the subscripts a, c and f represent the atomic state, the state of cavity and the state of fiber mode, respectively; $|j\rangle(j=0,1)$ denotes the Fock state with j photons; $|e_i\rangle_a$ stand for the ith$(i=1,2,\cdots,N,N+1)$ atom being in an excited state and other atoms being in ground states, $|g\rangle_a$ stand for all atom being in ground states; $|1_i\rangle_c$ means that the ith cavity is in one photon state, other cavities are in vacuum states; $|0\rangle_c$ denotes all cavities are in vacuum states; $|1_l\rangle_f$ is similar to $|1_i\rangle_c$, $|0\rangle_f$ is similar to $|0\rangle_c$. Then, the time evolution of the whole state vector is given by

$$|\varphi(t)\rangle = \sum_{i=1}^{N+1} A_i |\varphi_{ai}\rangle + \sum_{i=1}^{N+1} B_i |\varphi_{ci}\rangle + \sum_{l=1}^{N} C_l |\varphi_{fl}\rangle \tag{3}$$

where t denotes time, A_i, B_i and C_l are the expansion coefficients, and $\sum_{i=1}^{N+1}(|A_i|^2+|B_i|^2)+\sum_{l=1}^{N}|C_l|^2=1$. The state vector $|\varphi(t)\rangle$ obeys following the schrödinger equation

$$\mathrm{i}\frac{\partial}{\partial t}|\varphi(t)\rangle = H_{\mathrm{I}}|\varphi(t)\rangle \tag{4}$$

using the initial condition, we obtain by solving the Eq. (4)

$$\begin{cases} A_1 = \dfrac{1}{N+1}\cos(gt) + \dfrac{NJ^2}{\alpha^2} + \dfrac{Ng^2}{(N+1)\alpha^2}\cos(\alpha t) \\ A_2 = A_3 = A_4 = A_5 = A_6 = \cdots = A_{N+1} = -\dfrac{1}{N+1}\cos(gt) + \dfrac{J^2}{\alpha^2} + \dfrac{g^2}{(N+1)\alpha^2}\cos(\alpha t) \\ B_1 = -i\dfrac{1}{N+1}\sin(gt) - i\dfrac{Ng}{(N+1)\alpha}\sin(\alpha t) \\ B_2 = B_3 = B_4 = B_5 = B_6 = \cdots = B_{N+1} = i\dfrac{1}{N+1}\sin(gt) - i\dfrac{g}{(N+1)\alpha}\sin(\alpha t) \\ C_1 = C_2 = \cdots = C_N = -\dfrac{Jg}{\alpha^2} + \dfrac{Jg}{\alpha^2}\cos(\alpha t) \end{cases} \tag{5}$$

here we use the notation $\alpha = \sqrt{g^2+(N+1)J^2}$.

2 GQD between two atoms

In order to quantify the quantum correlation between the two subsystems, in Ref.[10] DAKIC B et al introduced GQD. The analytical expression of GQD is

$$D(\rho) = \frac{1}{4}(\|\boldsymbol{a}\|^2 + \|\boldsymbol{T}\|^2 - k_{\max}) \tag{6}$$

where

$$\begin{cases} a_i = \mathrm{Tr}\boldsymbol{\rho}(\sigma_i \otimes \boldsymbol{I}) \\ \| \boldsymbol{a} \|^2 = \sum_{i=1}^{3} \boldsymbol{a}_i^2 \\ \boldsymbol{T}_{ij} = \mathrm{Tr}\boldsymbol{\rho}(\boldsymbol{\sigma}_i \otimes \boldsymbol{\sigma}_j) \\ \| \boldsymbol{T} \|^2 = \mathrm{Tr}(\boldsymbol{T}^{\mathrm{T}}\boldsymbol{T}) \end{cases} \tag{7}$$

here Tr denotes tracing, $\boldsymbol{\rho}$ is the density matrix, $\boldsymbol{I}$ is identity matrix, $\boldsymbol{\sigma}_i (i = x, y, z)$ is the usual Pauli matrix, $\boldsymbol{a} = (a_1, a_2, a_3)^{\mathrm{T}}$ stands for a column vector, $\boldsymbol{T} = \{\boldsymbol{T}_{ij}\}$ is the matrix with elements T_{ij}, $\| \boldsymbol{T} \|^2 = \mathrm{Tr}(\boldsymbol{T}^{\mathrm{T}}\boldsymbol{T})$, $k_{\max}$ is the largest eigenvalue of the matrix $\boldsymbol{K} = \boldsymbol{a}\boldsymbol{a}^{\mathrm{T}} + \boldsymbol{T}\boldsymbol{T}^{\mathrm{T}}$, superscript T denotes a transpose of vector or matrix.

In the present paper, we use GQD as a criterion of quantum correlation. Firstly, we discuss the GQD between atom1 and atom2. Using Eq. (3), in the atom-atom bases $\{|ee\rangle, |eg\rangle, |ge\rangle$ and $|gg\rangle\}$, we obtain the density matrix $\boldsymbol{\rho}_{12}$ of atom1 and atom 2 subsystem

$$\boldsymbol{\rho}_{12} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & |A_1|^2 & A_1 A_2^* & 0 \\ 0 & A_2 A_1^* & |A_2|^2 & 0 \\ 0 & 0 & 0 & 1 - |A_1|^2 - |A_2|^2 \end{bmatrix} \tag{8}$$

Combining Eq.(7)and Eq.(8), we get

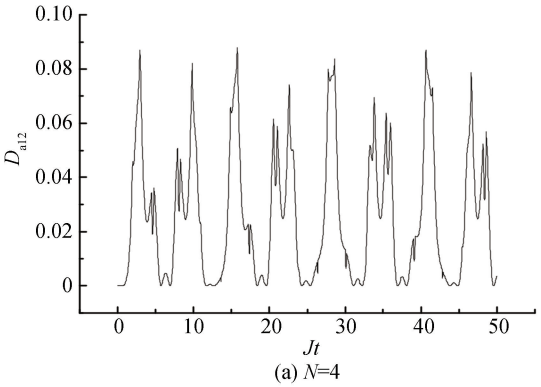
$$\begin{cases} a_1 = a_2 = 0 \\ a_3 = 2|A_1|^2 - 1 \\ T_{11} = 2A_1 A_2 = T_{22} \\ T_{33} = 1 - 2(|A_1|^2 + |A_2|^2) \end{cases} \tag{9}$$

other element T_{ij} equals zero. From Eq.(6) and Eq.(9), the GQD between atom1 and atom2 can be easily computed as

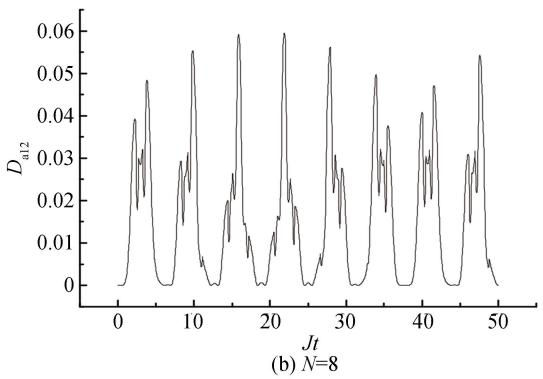
$$D_{a12} = \frac{1}{4}[a_3^2 + 2T_{11}^2 + T_{33}^2 - \max(T_{11}^2, T_{33}^2 + a_3^2)] \tag{10}$$

2.1 The influence of N on GQD between two atoms

In order to discuss the influence of the number of coupled cavities on GQD between two atoms, we set $g = J$. When N equals 4, 8, 12 and 16, respectively, D_{a12} as a function of the scale time Jt is plotted in Fig. 2. It is shown that D_{a12} exhibits irregular oscillation, and the peaks of curves decrease as N increases, and so do the averages of D_{a12}. This shows that the GQD between atom1 and atom2 is weakened with the increasing of N. Similarly, in the case of the same parameter as before, the GQD between atom2 and atom3 is exhibited in Fig. 3. We can clearly see from Fig. 3 that GQD between atom2 and atom3 is also weakened with the increasing of N. This can be qualitatively explained as follows: according to the symmetry of the system, the probabilities of atom2, atom 3, …, atom $N+1$ sharing the excitation number of system are the same, then the probability of atom2 sharing the excitation number decreases as N increases. Therefore, the GQD between two atoms is weakened with the increasing of N. For example, in the $[0, 50]$ region, the calculation results of the probabilities average of atom2 sharing the excitation number $\bar{A}_2^2$ are: when N equals 4, $\bar{A}_2^2$ equals 0.048 95; when N equals 8, $\bar{A}_2^2$ equals 0.016 32; when N equals 12, $\bar{A}_2^2$ equals 0.008 12; and when N equals 16, $\bar{A}_2^2$ equals 0.004 85.



(a) N=4



(b) N=8

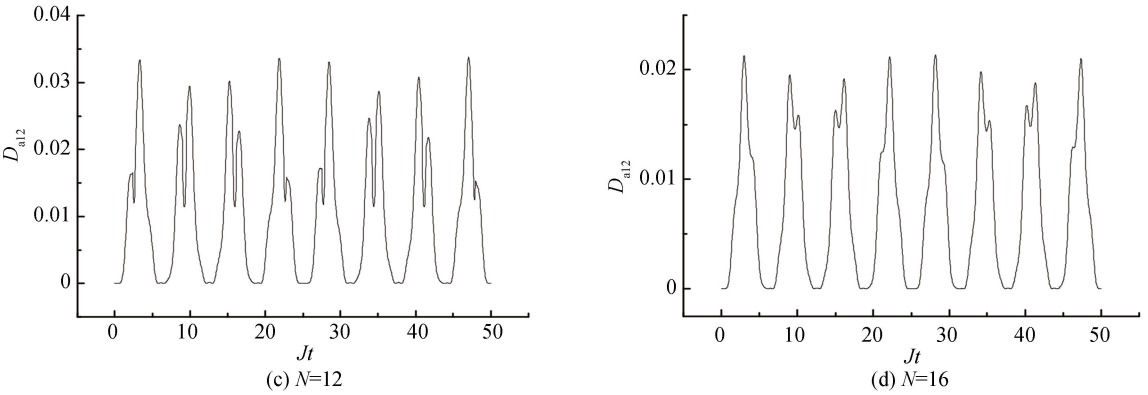


Fig.2 The time evolution of D_{a12} with the scaled time Jt

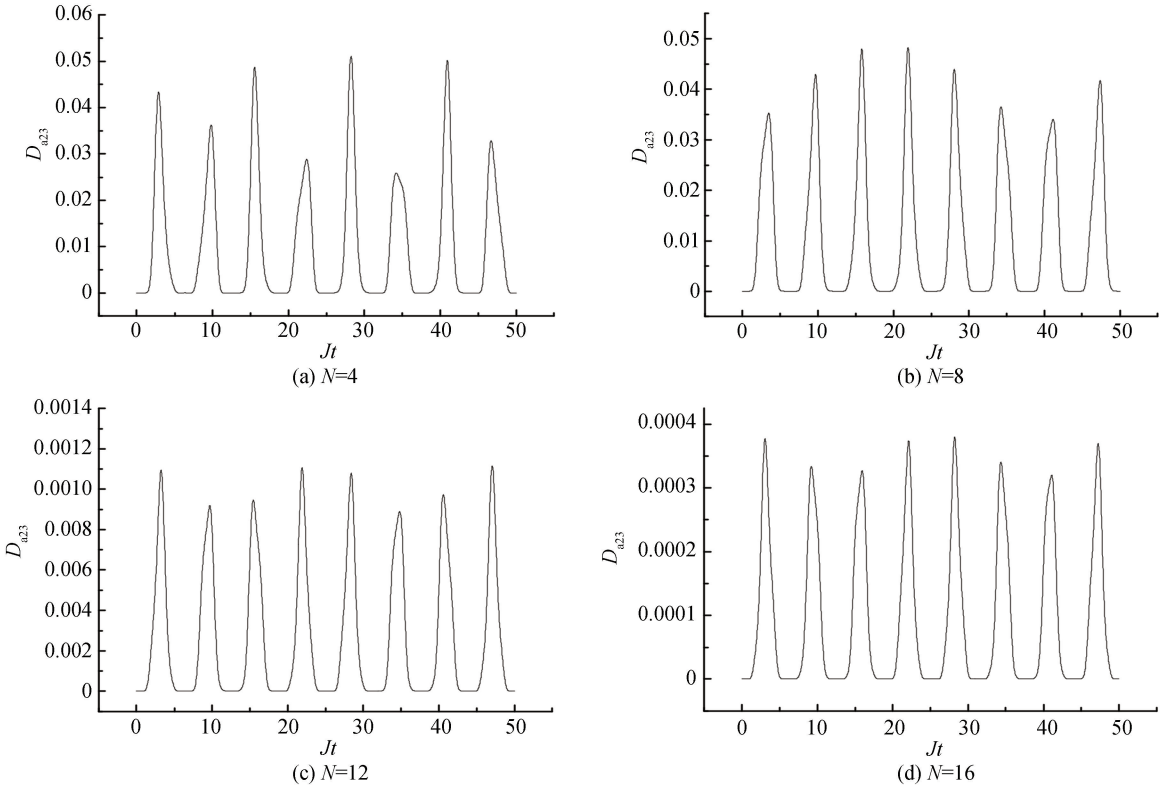


Fig.3 The time evolution of D_{a23} with the scaled time Jt

2.2 The influence of g on GQD between two atoms

Assuming that $N=8$, the atom-cavity coupling constant g equals $0.1J$, $0.5J$, J, $2.0J$, $5.0J$ and $10.0J$, respectively, we plot the evolution of D_{a12} with the scaled time Jt in Fig. 4. As shown in Fig.4, as the coefficient g increases, D_{a12} exhibits a quasi-periodic oscillation in the beginning; then it displays an irregular oscillation, finally it displays a quasi-periodic oscillation when g is larger than a certain value. From Eq. (9) and Eq. (10), we know that D_{a12} depends on expansion coefficients A_1 and A_2. They are all the superposition of cosine functions with the angular frequency α or g. As $g \ll J$, $A_1 \to \frac{1}{N+1}\cos(gt)+\frac{NJ^2}{\alpha^2}$, $A_2 \to -\frac{1}{N+1}\cos(gt)+\frac{J^2}{\alpha^2}$; As $g \gg J$, $\alpha \to g$. Therefore, in both cases either A_1 or A_2 is transformed into a cosine function of a single angular frequency. This leads that the evolution of D_{a12} shows a quasi-periodic oscillation. On the other hand, the averages of curves decrease with the increasing of coupling constant g. When g equals $0.5J$, J, $2.0J$ and $5.0J$, the average $\bar{D}_{a12}$ equals 0.021 28, 0.015 29, 0.009 12 and 0.005 82, respectively. This shows that GQD between two atoms is weakened with the increasing of

the atom-cavity coupling constant. Physically, this result can be understood as follow: the probabilities of the cavity modes being excited increase as the coupling coefficient g increases. This leads that the probabilities of atoms sharing the excitation number of system decrease. Thus, the GQD between atoms is weakened.

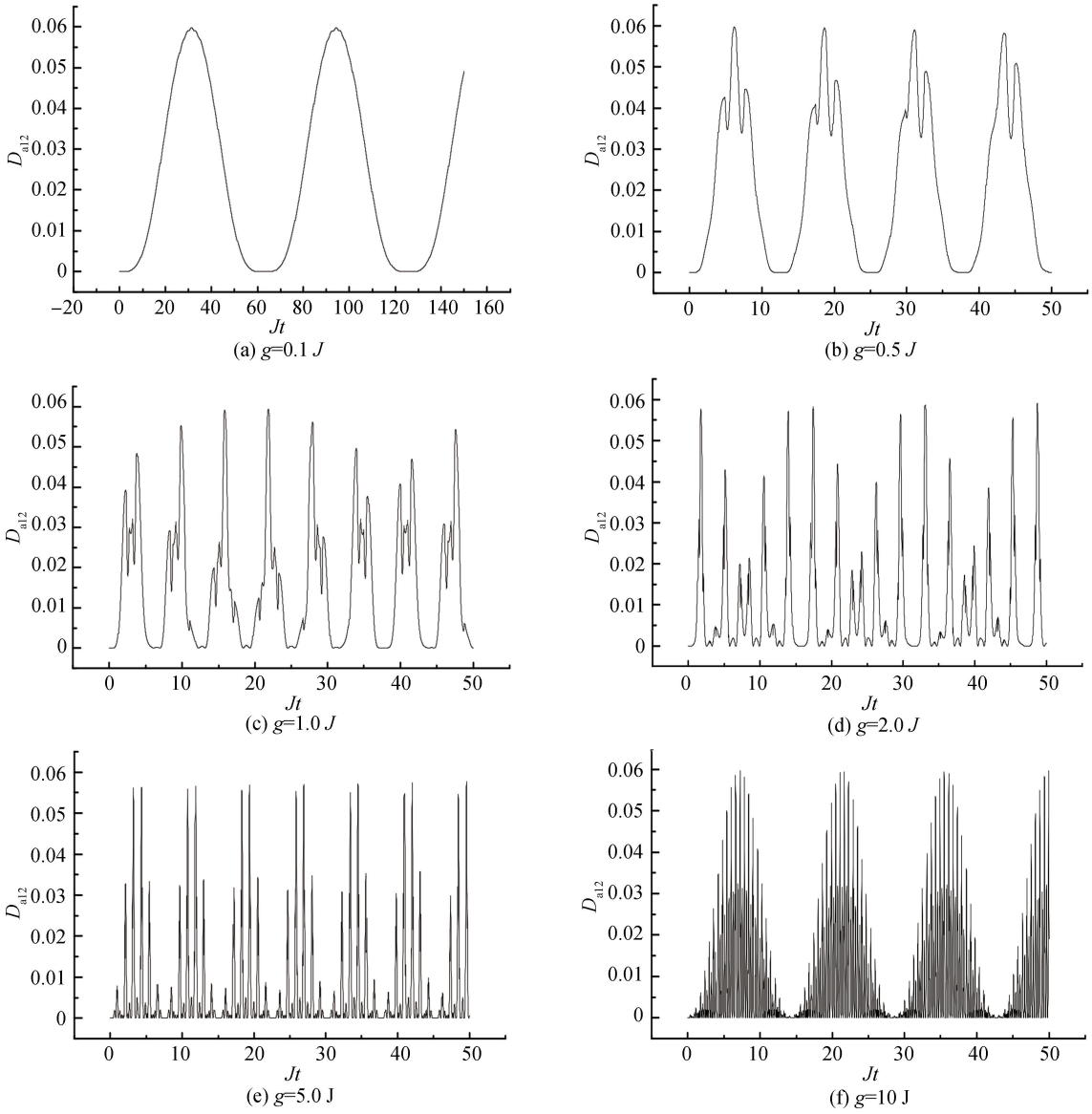


Fig.4 The time evolution of D_{a12} with the scaled time Jt

3 GQD between two cavities

It is similar to the calculation of GQD between two atoms in Sec.2. The density matrix of cavity1 and cavity2 subsystem can be written as

$$\boldsymbol{\rho}_{c12}=\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & |B_1|^2 & B_1B_2^* & 0\\ 0 & B_2B_1^* & |B_2|^2 & 0\\ 0 & 0 & 0 & 1-|B_1|^2-|B_2|^2\end{bmatrix} \tag{11}$$

Combining Eq. (7) and Eq. (11), we derive

$$\begin{cases} a_{c1}=a_{c2}=0 \\ a_{c3}=2\,|B_1|^2-1 \\ T_{c11}=2B_1B_2=T_{c22} \\ T_{c33}=1-2(|B_1|^2+|B_2|^2) \end{cases} \tag{12}$$

other element T_{cij} equals zero. Similar to the calculation of Eq. (10), the GQD between cavity1 and cavity2 can be derived as

$$D_{c12}=\frac{1}{4}[a_{c3}^2+2T_{c11}^2+T_{c33}^2-\max(T_{c11}^2,T_{c33}^2+a_{c3}^2)] \tag{13}$$

3.1 The influence of N on GQD between two cavities

Again, set $g=J$, the evolutions of D_{c12} versus the scaled time Jt for different N are plotted in Fig. 5. From Fig. 5, we can see that the evolution of D_{c12} is similar to that of D_{a12}, the peaks and the averages of curves decrease as N increases. This means that the GQD between two cavities is weakened with the increasing of N. The reason is as follows: the probabilities of cavity2, cavity 3, … , cavity $N+1$ sharing the excitation number of system are the same, then the probability of cavity2 sharing the excitation number decreases as N increases. This causes the GQD between two cavities to decrease.

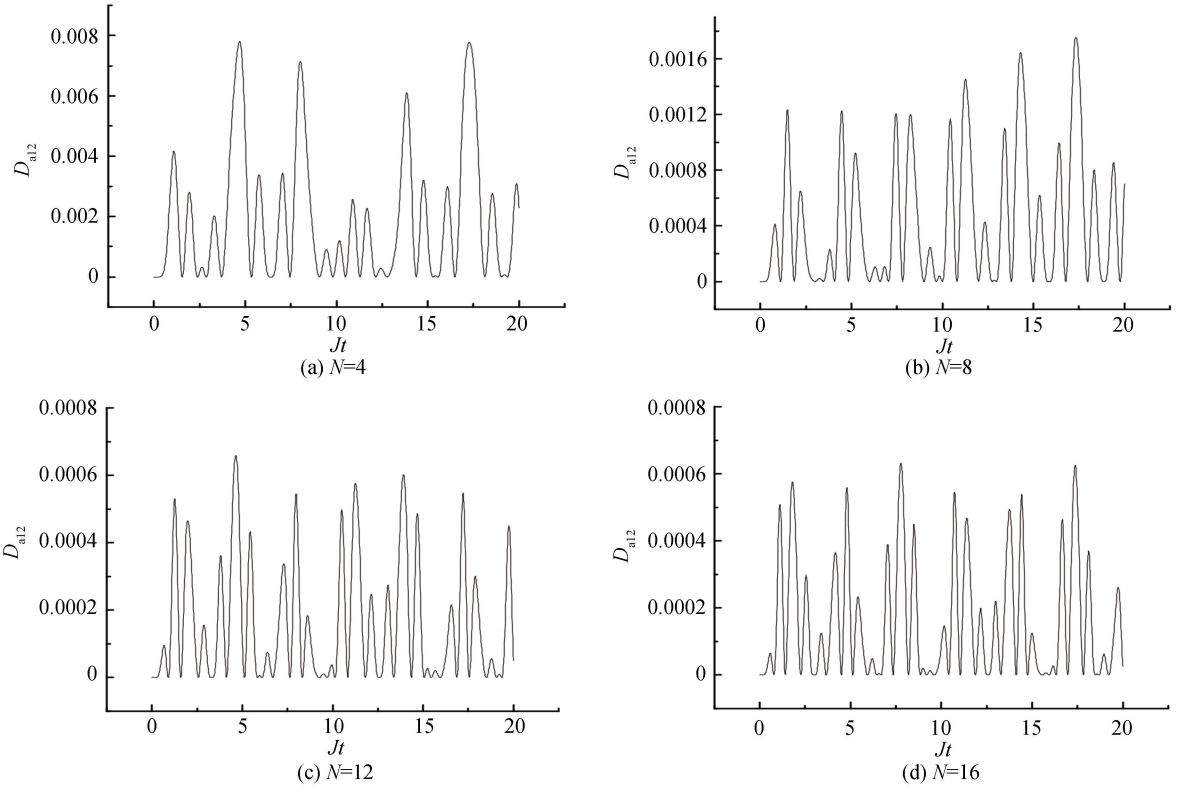


Fig.5 The time evolution of D_{c12} with the scaled time Jt

3.2 The influence of g on GQD between two cavities

When N equals 8 and the atom-cavity coupling constant g equals some given values, the evolutions of GQD (D_{c12}) between cavity1 and cavity2 versus the scaled time Jt are plotted in Fig. 6. As seen from Fig. 6, as g increases, the curves show a transition from quasi-periodic oscillation to irregular oscillation and then to quasi-periodic oscillation. The reason is similar to that in section 2.2, i.e., when $g \ll J$ or $g \gg J$, B_1 and B_2 are all transformed into cosine functions of a single angular frequency. But the peaks of the curves increase as g increases, and so do the averages of D_{c12}. This shows that GQD between two cavities is strengthened with the increasing of g.

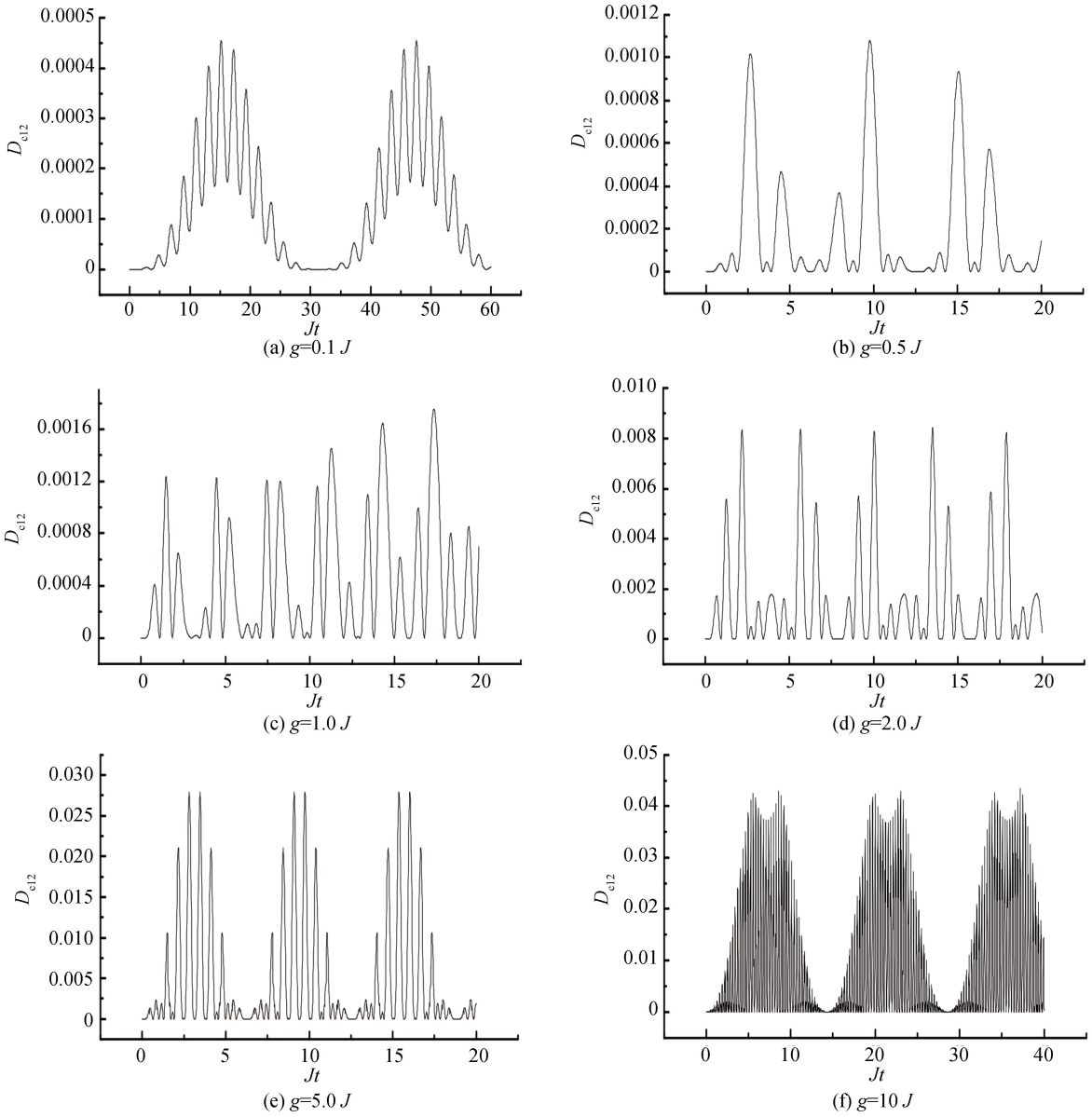


Fig.6 The time evolution of D_{c12} with the scaled time Jt

4 Conclusion

In conclusion, we introduce the coupled-cavity model with the center. It consists of $N+1$ single-mode cavities, and each cavity contains a two level atom. Cavity1 is at the center of the system, and is coupled to the remaining N cavities through N fibers. We consider the situation that atom resonantly interacts with cavity field via a one-photon hopping. Under one-excitation condition, the evolution of state vector of the system is derived. Using the numerical calculation, we plot the evolution curves of GQD between two atoms and between two cavities. The calculation results show: firstly, the peaks of curves GQD between two atoms and that between two cavities all decrease with the increasing of the number of coupled cavities, and so do the averages of curves; secondly, the averages of curves of GQD between two atoms decrease with the increasing of atom-cavity coupling constant, but the averages and the peaks of curves of GQD between two cavities increase with the increasing of atom-cavity coupling constant. These results show that GQD between two atoms and that between two cavities are weakened with the number of coupled cavities. On the other hand, as the atom-cavity coupling constant increases, GQD between two atoms is weakened, but GQD between two cavities is strengthened.

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