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Research Article

Field Squeezing in a Quantum-Dot Molecule Jaynes-Cummings Model

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We investigate the field squeezing in a system composed of an initial coherent field interacting with two quantum dots coupled by electron tunneling. An approximate quantum-dot molecule Jaynes-Cummings model describing the system is given, and the effects of physical quantities, such as the temperature, phonon-electron interaction, mean photon number, field detuning, and tunneling-level detuning, are discussed in detail.

1. Introduction

Thanks to the rapid progress of nanotechnologies, the exploration of the quantum-dot system, a mesoscopic synthetic material with a quantum confinement configuration, has provided a versatile tool for the simulation of many interesting phenomena in condensed matter physics [1, 2], among which, the quantum-dot molecule (QDM), formed from an asymmetric double quantum-dot system coupled by tunneling, has attracted much attention recently. New trends in nanotechnology even enable us to manipulate this kind of QDM using the external controlment, that is, electric field or optical field.

The interaction between atoms and field, an intriguing topic in modern quantum optics, yields many novel properties of the optical system. Based on the study of Jaynes-Cummings model, a fully quantum mechanical model and one of the few exactly solvable models that describes an atom in an external field, many studies have been made including the generalization of the model, such as applying the initial conditions [3], considering the dissipation and damping [4], multilevel of atoms, and multimode field [5, 6]. Many nonclassical effects have been investigated within the framework of this model, like Rabi oscillations, collapse-revival phenomenon, sub-Poissonian photon statistics, and squeezed state of the radiation field [7, 8]. Specifically, the squeezed state of light, a pure quantum effect without classical parallelism, has attracted much attention in these decades [9]; it can be widely used in the exploration of gravitational wave [10, 11], nonlinear optics [12], quantum information [13], quantum communication [14], and even precision metrology [15].

For its artificial nature and properties similar to natural atoms and molecules, the QDM, an ideal candidate for the mimic of atoms interacting with external fields, has been studied extensively, because its levels could be controlled conveniently and tuned easily [16]. However, the QDM is often surrounded by the solid matrix which means that the electrons are inevitably coupled with phonons and it hints that the electron-phonon interaction cannot be neglected during the tunneling. Therefore the zero-temperature treatment is not always valid and the temperature of the environment has a significant role [17]. Although the population of all states has been analyzed, the squeezing effect of the QDM has not been investigated. In this paper we consider the squeezing of a single-mode field interacting with a QDM and study analytically and numerically how the squeezing depends on various tunable parameters of the system.

This paper is arranged as follows; the next section gives the model of the external field interacting with a QDM and the equations describing the system are given; in Section 3 the squeezing of the optical field is considered from different perspectives while Section 4 gives the discussion and summary.

2. The Model

Consider a pulsed laser field interacting with a QDM with the configuration that state $|0\rangle$ is the ground state without excitation while states $|1\rangle$ and $|2\rangle$ are excited states representing an electron in the left dot and one hole in the left dot [16]. For the sake of the far off-resonance of the valence band levels of two dots, other states are hardly coupled with these states; hence they are neglected here for simplicity without the loss of generality. The single-mode field with frequency ω couples the states $|0\rangle$ and $|1\rangle$ with detuning δ; states $|0\rangle$ and $|2\rangle$ are uncoupled in the time scale we consider here; quantum electronic tunneling T_e between states $|1\rangle$ and $|2\rangle$ can be controlled by voltage.

Because of the low-enough temperature considered here, most of the electron-phonon interaction is the result of the deformation of the potential while the coupling constant g_k of this interaction is determined by the quantum-dot material and lattice configuration. Using the assumption that other factors causing the interaction are negligible, hence all the phonon-electron interactions can be treated as caused by the potential deformation [18]. So it is reasonable to apply the Einstein model with all the phonons having the same frequency $\omega_k = \omega_0$. Under the dipole approximation and the rotating-wave approximation, the Hamiltonian of the system in the interaction picture reads ($\hbar = 1$) [19]:

$$\begin{aligned} H_I &= T_e \left(R_{21} e^{-i\omega_{12} t} + R_{21} e^{i\omega_{12} t} \right) e^{-S} \\ &\quad + \lambda \left(\hat{a}^{\dagger} R_{01} e^{-i(\delta-\Delta)t} + \hat{a} R_{10} e^{i(\delta-\Delta)t} \right) e^{-S/2}, \end{aligned} \tag{1}$$

where $\Delta = \sum_k g_k^2/(4\omega_k)$ and detuning $\delta = \omega_{10} - \omega$, $\omega_{12} = \omega_1 - \omega_2$. The item representing the phonon effects, which has the expression $S = 2\sum_k (N + 1/2)(g_k/2\omega_k)^2 = 2(N + 1/2)\sum_k (g_k^2/4\omega_k^2) = 2(N + 1/2)G$, where G is Huang-Rhys factor expressed as $\sum_k (g_k^2/4\omega_k^2)$ [20], corresponds to the electron-phonon interaction with temperature-dependent phonon population $N = 1/(e^{\omega_k/T} - 1)$. In Hamiltonian (1), $R_{ij} = |i\rangle\langle j|$ $(i, j = 0, 1, 2)$ corresponds to the transition operators of the QDM, T_e is tunneling matrix element between the left and right dots, λ is the field-QDM coupling constant, and $\hat{a}^{\dagger}$ ($\hat{a}$) is the creation (annihilation) operator of the optical field satisfying $[\hat{a}, \hat{a}^{\dagger}] = 1$. In the model, both ω_{12} and T_e can be manipulated by an external voltage.

We suppose that initially the QDM is in the ground state $|0\rangle$ and the system is described as

$$|\psi(0)\rangle = |\psi_A(0)\rangle \otimes |\psi_F(0)\rangle = \sum_{n=0}^{\infty} F_n |0, n\rangle, \tag{2}$$

where $|\psi_F(0)\rangle$ is the arbitrary optical field, and then the state vector of the system at time t takes the form

$$|\psi(t)\rangle = \sum_n \left[c_n(t) |2, n\rangle + b_n(t) |1, n\rangle + a_{n+1}(t) |0, n+1\rangle \right]; \tag{3}$$

hence the substitution of state vector (3) into Schrödinger's equation yields a set of differential equations describing the expanding coefficients as

$$\begin{aligned} i \begin{pmatrix} \dot{a}_{n+1} \\ \dot{b}_n \\ \dot{c}_n \end{pmatrix} &= \begin{pmatrix} 0 & \lambda\sqrt{n+1} e^{-i(\delta-\Delta)t} e^{-S/2} & 0 \\ \lambda\sqrt{n+1} e^{i(\delta-\Delta)t} e^{-S/2} & 0 & T_e e^{i\omega_{12} t} e^{-S} \\ 0 & T_e e^{-i\omega_{12} t} e^{-S} & 0 \end{pmatrix} \\ &\quad \times \begin{pmatrix} a_{n+1} \\ b_n \\ c_n \end{pmatrix}. \end{aligned} \tag{4}$$

The combination of the above coupled equations leads to a set of decoupled equations and their solutions could be obtained with the initial conditions $a_{n+1}(0) = F_{n+1}$ and $b_n(0) = c_n(0) = 0$.

Analytically, the solutions can be directly given when phonon effect is not included for $\omega_{12} = \delta$, $\Delta = 0$, $\delta = \Delta$, and $\omega_{12} = 0$; or the external optical field is in resonance with the zero-phonon line while the state $|1\rangle$ is in resonance with state $|2\rangle$ which indicates that the coherent population oscillations can persist, similar to the case without phonon effect, and expect that the expression in the Rabi like oscillating frequency and the interdot tunneling rate is renormalized by the exponents of $-S/2$ and $-S$ [17]. We can see that electron-phonon coupling can make a significant contribution to the light-QDM interaction which can make the oscillation of the population of the state more drastic than that without the phonon effect [19].

3. Squeezing of the System

We introduce two orthogonal quadrature amplitude operators $\hat{X}_1 = (1/2)(\hat{a} + \hat{a}^{\dagger})$ and $\hat{X}_2 = (1/2i)(\hat{a} - \hat{a}^{\dagger})$ satisfying the commutation relation $[\hat{X}_1, \hat{X}_2] = i/2$ which lead to

$$(\Delta\hat{X}_1)^2 (\Delta\hat{X}_2)^2 \geq \frac{1}{16} \tag{5}$$

according to Heisenberg's uncertainty principle, with $(\Delta\hat{X}_i)^2 = \langle\hat{X}_i^2\rangle - \langle\hat{X}_i\rangle^2$ $(i = 1, 2)$. The state of the field is said to be squeezed when one of the amplitudes $\hat{X}_i$ satisfies the relation $Q_i = (\Delta\widehat{X}_i)^2 - 1/4 \leq 0$ $(i = 1, 2)$. According to (3) we express the squeezing parameters for the two amplitudes as

$$\begin{aligned} Q_1 = {} & \frac{1}{4}\sum_n \sqrt{(n+1)(n+2)} \\ & \times \left(c_n^* c_{n+2} + b_n^* b_{n+2} + a_n^* a_{n+2} \right. \\ & \left. + c_{n+2}^* c_n + b_{n+2}^* b_n + a_{n+2}^* a_n\right) \\ & + \frac{1}{4}\sum_n (2n+1)\left(c_n^* c_n + b_n^* b_n + a_n^* a_n\right) \\ & - \frac{1}{4}\left[\sum_n \sqrt{n+1} \right. \\ & \times \left(c_n^* c_{n+1} + b_n^* b_{n+1} + a_n^* a_{n+1} \right. \\ & \left.\left. + c_{n+1}^* c_n + b_{n+1}^* b_n + a_{n+1}^* a_n\right)\right]^2 - \frac{1}{4}, \end{aligned} \tag{6a}$$

$$\begin{aligned} Q_2 = {} & -\frac{1}{4}\sum_n \sqrt{(n+1)(n+2)} \\ & \times \left(c_n^* c_{n+2} + b_n^* b_{n+2} + a_n^* a_{n+2} + c_{n+2}^* c_n \right. \\ & \left. + b_{n+2}^* b_n + a_{n+2}^* a_n\right) \\ & + \frac{1}{4}\sum_n (2n+1)\left(c_n^* c_n + b_n^* b_n + a_n^* a_n\right) - \frac{1}{4}. \end{aligned} \tag{6b}$$

Making the assumption that the optical field is initially in a monochromatic coherent state $F_n = e^{-\bar{n}/2}\bar{n}^{n/2}e^{in\beta}/\sqrt{n!}$, where the mean photon number of the coherent fields $\bar{n} = |\alpha|^2$ and β is the phase, $\beta = 0$ is chosen in the following.

In order to investigate the squeezing in detail, we consider several factors that affect squeezing behaviors. First the temperature effect of the system is discussed, where $G = 0.01$ represents the electron-phonon interaction and $\Delta = \delta = 0.05\omega$, $\omega_{12} = 0$, $\lambda = 0.2\omega$, and $T_e = 0.2\omega$; we choose different values of temperature T which directly modify the phonon population. In Figure 1 we show that, with the evolution of dimensionless time ωt, the curves change significantly with the increase of temperature T. In the zero-temperature case (Figure 1(a)), the envelope of oscillation is sinusoidal but with a significant damping. In the time scale shown in the figure, there are more than three time regions where the system reaches squeezing for Q_1; however, the number of time ranges for the squeezing of Q_2 is even more but the amplitude of Q_2 is smaller than that of Q_1. We also notice that the oscillation frequencies of the squeezing parameters at higher temperatures are smaller than at lower ones. It is apparent that, for higher temperatures, $T = 50\omega_0$ and $T = 100\omega_0$, chances for the squeezing decrease for both Q_1 and Q_2. The physical explanation is obvious: the quantum properties are weakened for the increase of temperature; being a typical quantum phenomenon, squeezing is strongly suppressed by higher temperature.

Now we set a fixed temperature $T = 10\omega_0$ (use this temperature hereafter) and assume the detuning $\delta = \omega_{12} = 0$, electron-phonon interaction factor $G = 0.01$, interdot tunneling $T_e = 0.2\omega$, and field-QDM coupling $\lambda = 0.1\omega$; then Figure 2 shows that when Δ varies from 0.01ω to 0.05ω the squeezing of the states significantly decreases, indicated by both Q_1 and Q_2 curves. The biggest squeezing appears for the smallest Δ; we find that the maximum squeezing reaches 24% (12%) for Q_1 (Q_2) when $\Delta = 0.01\omega$ while the squeezing reduces to 2% (2.4%) when Δ increases to 0.05ω. Also we find that, with the growth of Δ, the periodicity vanishes for long time scale (not shown in the figure) which means that the gradual enhancement phonon effect will lead to the irregular oscillations of the squeezing curves. The biggest squeezing happens around $\omega t = 40$ (20) for Q_1 (Q_2) at small Δ and, after the time around $\omega t = 40$, the system will not go back to the squeezed state any more.

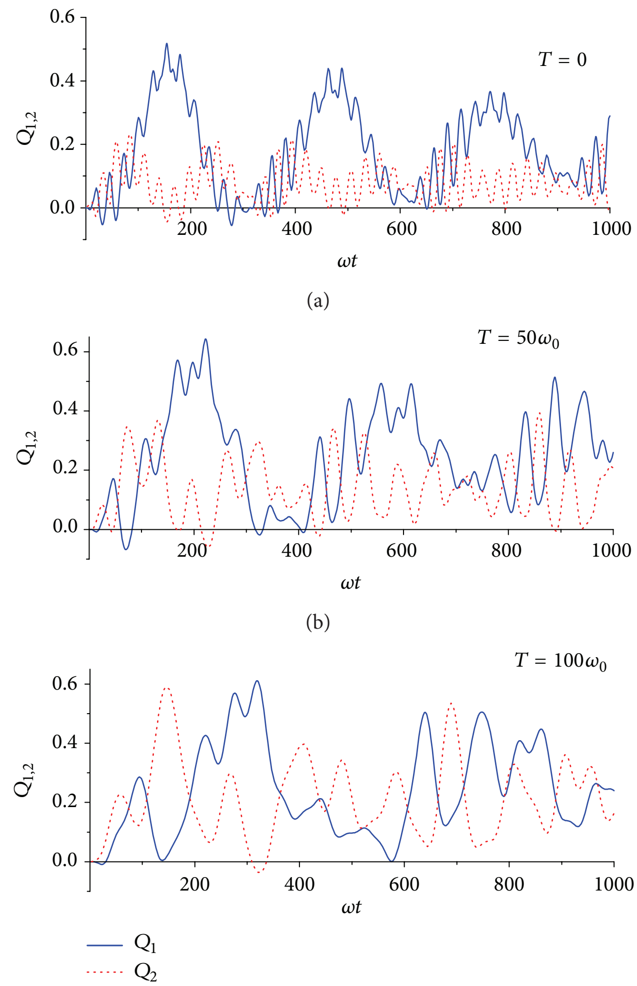

Figure 1: (Color online) $Q_{1,2}$ versus dimensionless time ωt at different temperature when $\Delta = \delta = 0.05\omega$, $\omega_{12} = 0$, $G = 0.01$, $T_e = 0.2\omega$, and $\lambda = 0.2\omega$ are considered.

It is interesting to speculate how the squeezing changes with detuning ω_{12} at fixed temperature and its time-dependent behaviors. In this case, we choose $\Delta = 0$ and ω_{12} is ranging from 0.01ω to 0.1ω; $T_e = 0.2\omega$, $T = 10\omega_0$, and $\lambda = 0.1\omega$ are fixed as previously indicated. Noticing from

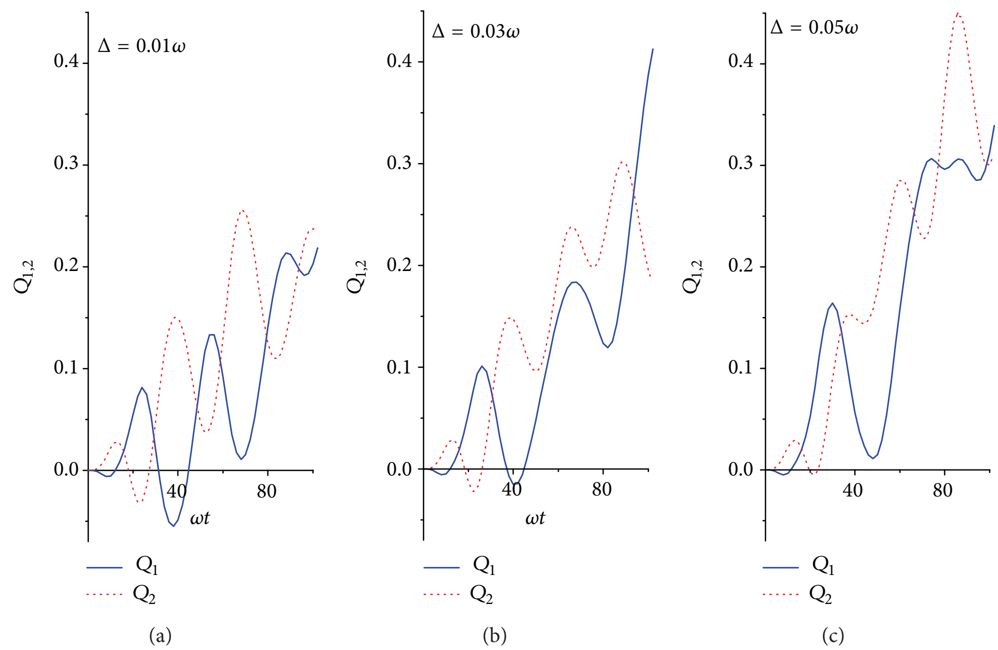

FIGURE 2: (Color online) $Q_{1,2}$ versus dimensionless time ωt for different Δ when $T = 10\omega_0$, $\delta = \omega_{12} = 0$, $G = 0.01$, $T_e = 0.2\omega$, and $\lambda = 0.1\omega$ are chosen.

Figure 3 clearly that squeezing decreases with the increase of ω_{12}, the biggest squeezing for Q_1 (Q_2) in $\omega_{12} = 0.01\omega$ is 24% (12%) while it decreases to 12% (8%) when $\omega_{12} = 0.03\omega$, and notice, from Figure 3(d), however, there is almost no squeezing when $\omega_{12} = 0.1\omega$ right after the system evolves. The curves in the figure also show that the squeezing of Q_1 is stronger than Q_2 regardless of ω_{12} being small or big.

Previously we suppose that one or two parameters of δ, ω_{12}, and Δ are zero and get some properties of the squeezing in different regimes. Now, to study the general case that both δ and ω_{12} are nonzero and effect of Δ is included, we show the squeezing parameters in Figure 4 with three sets of values for ω_{12} less than, equal to, and greater than δ separately. From the figure we find that when $\omega_{12} < \delta$, the squeezing of Q_2 is greater than Q_1 and the biggest squeezing for Q_1 (Q_2) is about 4% (8%); then with the continuous increasing of ratio ω_{12}/δ we find that squeezing for Q_2 is suppressed and eventually vanishes when $\omega_{12} = 3\delta$. Notice that there are two regions for X_1 being squeezed when $\omega_{12} < \delta$ while the number of regions of squeezing reduces to one if the ratio of ω_{12}/δ increases; besides, the squeezing depth and duration of the first region nearly remain unchanged.

Despite the cases that the mean photon number $\overline{n} = 1$ discussed above, it is significant to consider the effect of mean photon number $\overline{n}$ on the squeezing; we choose $\Delta = \delta$ and states $|1\rangle$ and $|2\rangle$ are in resonance. When $\overline{n} = 1$, we find that the oscillation for $Q_{1,2}$ is periodical with damping in the time range and the squeezing parameter evolves regularly; the biggest squeezing for Q_1 is around 25% happening at $\omega t = 38$ while around 21% at $\omega t = 170$ for Q_2. With the time evolution, the field can still be squeezed in the long time scale. When it comes to the bigger $\overline{n}$ cases, we find that, after the system reaches squeezing, the curves almost linearly increase monotonically, which correspond to the so-called Cummings collapse region [21, 22]. We find that the biggest squeezing will be higher than that in $\overline{n} = 1$ case. If we want to obtain the biggest squeezing, the laser-QDM interaction time will be longer for larger $\overline{n}$.

The discussion and results above are reliable and they can be implemented in labs. Now we consider the parameters that are used in InAs self-assembled QDM under coherent laser excitation and find that the squeezing for weak and strong tunneling is 6.4% and 22%, respectively, where we choose $\omega =$ 1.6 eV, $\lambda = 1 \times 10^{-3}$ eV, $\omega_{12} = 0.1 \times 10^{-3}$ eV, $\delta = 0.1 \times 10^{-3}$ eV, $\Delta = 0$, $T_e = 0.1\times10^{-3}$ eV (weak tunnel), or 5×10^{-3} eV (strong tunnel) [23–28]; we find that the squeezing in weak tunneling is greater than that in strong tunneling case which shows that the coupling of the laser field and the QDM is equivalently weakened.

4. Conclusion

In this paper we have investigated the field squeezing of the quantum-dot molecule Jaynes-Cummings model. Using the appropriate approximation we give the Hamiltonian of the system describing the field-QDM interaction and solve the related equations afterwards. By analytical and numerical processes, we show influence of the various parameters of the system on the squeezing. We show that the squeezing generally decreases with time. It is shown that, because of the quantum nature being suppressed, the amount of squeezing becomes smaller as temperature rises, and the periodicity of the squeezing parameter curves is destroyed.

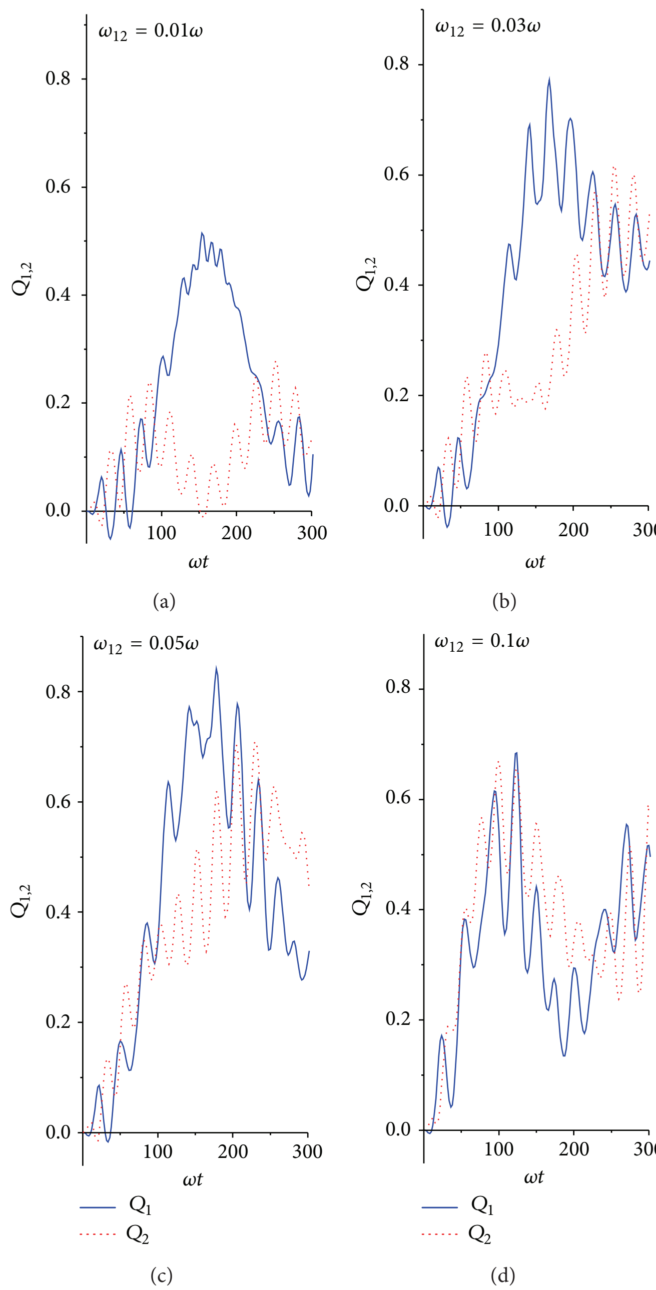

FIGURE 3: (Color online) $Q_{1,2}$ varies with dimensionless time ωt for different ω_{12}, when $\delta = \Delta = 0$, $T = 10\omega_0$, $T_e = 0.2\omega$, and $\lambda = 0.1\omega$ are chosen.

The squeezing vanishes rapidly when the phonon effect is enhanced which shows that the phonon effect is distinct in this field-QDM interaction model. Despite these factors, increasing the ratio of detuning ω_{12} to δ can weaken the squeezing. In addition, the initial mean phonon numbers can play an important role in the squeezing; the big number makes the squeezing behavior obscure. Compared with the atomic assembled counterpart, the QDM has its advantage that is more convenient for the experimental manipulation and this field-QDM model opens up the new possibility of studying the light squeezing and allows its use in tunable semiconductor quantum-dot system.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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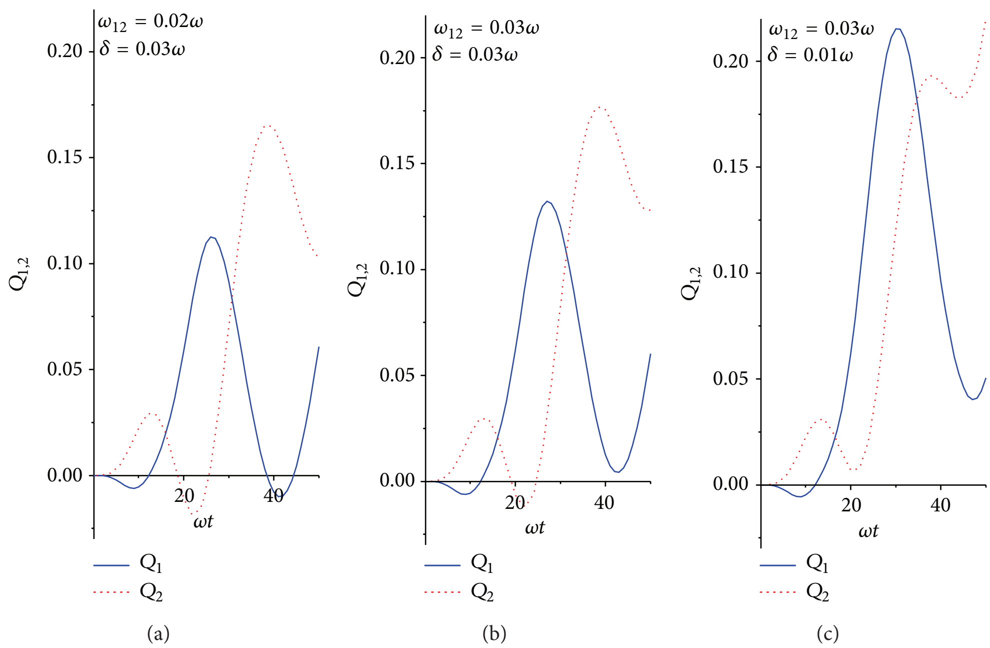

FIGURE 4: (Color online) $Q_{1,2}$ versus dimensionless time ωt for different detunings ω_{12} and δ with the same parameters chosen as previously.

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