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Inter-dot tunneling control of optical bistability in triple quantum dot molecules

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ABSTRACT

The behavior of optical bistability (OB) and optical multistability (OM) in a triple coupled quantum dot (QD) system is theoretically explored. It is found that the tunneling coupling between electronic levels has major effect on controlling the threshold and the hysteresis cycle shape of the optical bistability. The impact of incoherent pump field on the OB and OM behavior of such medium is then discussed. We realize that the threshold intensity reduces remarkably through increasing the rate of incoherent pumping. It is also demonstrated that the switch between OB and OM can be obtained just through proper adjusting the frequency detuning of probe field. It should be pointed that in this QD system we used tunneling instead of coupling lasers. These presented results may be applicable in real experiments for realizing an all-optical bistate switching or coding element in a solid-state platform.

1. Introduction

Coherence and quantum interference can lead to many kind of quantum optical phenomena such as electromagnetically induced transparency [1,2], lasing without inversion [3–5], light storage [6], multi-wave mixing [7–10], enhancing Kerr nonlinearity [11–14], optical soliton [15,16], optical bi- and multistability [17–20] and so on.

Optical bistability (OB) is one of the numerous manifestations arising from all-optical interactions. In optical bistability or multistability, an optical system has two or more than two stable states, most often represented by the intensity at the output of the system as a function of the input intensity. With the level of the output intensity determined by a certain operation on a light beam, a bi- or multistable system makes a decision in which state it will operate, acting as a switch for optical communications or optical data processing [21].

Since optical bistability (OB) has wide applications in all-optical switching and all-optical storage, it has been extensively studied theoretically and experimentally in various media [22–28]. Sheng et al. [28] have experimentally observed optical multistability (OM) in an optical ring cavity containing three-level Λ-type doppler-broadened rubidium atoms. They found that the shape of the OM curve can be significantly modified by changing the power of the control laser field. Bistabe behavior of Λ-type [29], V-type [30], and ladder-type [31] three-level atomic system has also been theoretically investigated. Wang et al. [32] have investigated the optical bistability and multistability in an Er^{3+}-doped ZrF_4–BaF_2–LaF_3–AlF_3–NaF optical fiber inside an optical ring cavity. They showed that the optical bistability and multistability can be easily controlled via tuning properly the parameters of the corresponding system. Previously, we have analyzed theoretically optical bistability (OB) and optical multistability (OM) in a medium consisting of four-level cascade-type cold atoms by means of a unidirectional ring cavity. We showed that by proper tuning of the radio- frequency (RF) field the threshold and the hysteresis cycle shape of OB and OM can be engineered.

Along with advances in quantum and nonlinear optics, fast development in the fabrication and control of mesoscopic quantum systems opens an avenue to investigate the optical analogs of a wide variety of quantum effects in condensed matter systems, due to the potentially important applications in optoelectronics and solid state information sciences. It has been shown that they can lead to gain without inversion [33], electromagnetically induced transparency (EIT) [34], optical bistability [35–36], Kerr nonlinearity [37,38], high electron localization [39–41], and so on.

Being easily controllable in size and in the energy levels spacing, quantum dot molecules (QDMs) are promising candidates for the above studies. In such molecules, an external electric field allows us to control the confining potential and the number of electrons or holes, as well as their mutual interaction. Many studies have been done on optical properties of QD systems [42–45]. For instance, Li et al. have proposed a method to control the gain, absorption and dispersion properties in an asymmetric double quantum dot nanostructure interacting with four optical

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fields [34]. In their another work [46], they have studied optical transmission properties of a combined system which is composed of a photonic crystal (PC) microcavity with low quality factor Q, a triple quantum dot (QD) embedded in cavity and two parallel waveguides. They demonstrated that low coupling strength between a cavity and a dot, by means of electron tunnel-induced coupling, can lead to a type of double-state controllable optical switching under the experimentally available parameter conditions.

In this paper, we investigate the OB and OM behavior of a QD molecule composed of three quantum dots by using the density matrix formalism. The results show that the optical bistability of this system is strongly dependent on tunneling couplings between electronic levels. The dependence of OB and OM on different controlling parameters of the system is then discussed. The controllability of OB and OM of this QD medium may be useful in building logic-gate devices for optical computing and quantum information processing and provide some new possibilities for solid-state quantum information science. It should be also pointed out that the OB comes essentially from the Kerr nonlinearity, thus solitons could form in those systems of demonstrating OB behaviors.

2. Model and equations

Fig. 1(a and b) shows the schematic of the setup and level configuration for the QD system under consideration. In this QD system and at nanoscale inter-dot separation, the hole states are localized, while the electron states remain rather delocalized. In absence of optical excitation, no excitons find inside all the QDs, condition represented by the state $|0\rangle$. When a laser field is applied, a direct exciton is created inside the QD1, which corresponds to state $|1\rangle$. The external electric field modifies the band profiles alignment, and allows the electron to tunnel from QD1 to the QD2 and QD3 forming the indirect excitons, which is denoted here as states $|2\rangle$ and $|3\rangle$. The tunnel barrier in TQDs can be controlled by placing a gate electrode between the neighboring dots. In the interaction picture, the Hamiltonian of this system in the rotating wave and dipole approximations can be given by ($\hbar = 1$).

$$H = \sum_{j=0}^{3} E_j |j\rangle\langle j| + \left[\left(\Omega_p e^{-i\omega_p t}|0\rangle\langle 1| + T_2|2\rangle\langle 1| + T_3|3\rangle\langle 1|\right) + H.C.\right] \tag{1}$$

where $E_j = \hbar\omega_j$ is the energy of state $|j\rangle$, a weak tunable probe field of frequency ω_p and Rabi-frequency $\Omega_p = \wp_{01}.e.E$ is applied for the transition $|0\rangle \rightarrow |1\rangle$. Here, $\wp_{01}, e, E$ denote the associated dipole transition-matrix element, the polarization vector and the electric-field amplitude of the laser pulse, respectively. Also, the coefficients T_2 and T_3 are the tunneling inter-dot coupling between QD1–QD2 and QD2–QD3, respectively.

Using the Liouville equation ($\dot{\rho} = -i/\hbar\,[H,\rho]$), we can easily obtain density matrix equation of the motion for the above QD system as

$$\begin{aligned}
\dot{\rho}_{10} &= i\Omega_p(\rho_{11}-\rho_{00}) + iT_2\rho_{20} + iT_3\rho_{30} - (i\delta_p + \gamma_{01} + r)\rho_{10},\\
\dot{\rho}_{20} &= iT_2\rho_{10} - i\Omega_p\rho_{21} - \left(\tfrac{i}{2}(\delta_p+\delta_2) + \gamma_{02}\right)\rho_{20},\\
\dot{\rho}_{30} &= iT_3\rho_{10} - i\Omega_p\rho_{31} - \left(\tfrac{i}{2}(\delta_p+\delta_3) + \gamma_{03}\right)\rho_{30},\\
\dot{\rho}_{21} &= iT_2(\rho_{11}-\rho_{22}) - i\Omega_p\rho_{20} - iT_3\rho_{23} - \left(\tfrac{i}{2}(\delta_2-\delta_p) + \gamma_{12}\right)\rho_{21},\\
\dot{\rho}_{31} &= iT_3(\rho_{11}-\rho_{33}) - i\Omega_p\rho_{30} - iT_2\rho_{32} - \left(\tfrac{i}{2}(\delta_3-\delta_p) + \gamma_{13}\right)\rho_{31},\\
\dot{\rho}_{32} &= iT_3\rho_{12} - iT_2\rho_{31} - \left(\tfrac{i}{2}(\delta_3-\delta_2) + \gamma_{23}\right)\rho_{32},\\
\dot{\rho}_{11} &= i\Omega_p(\rho_{01}-\rho_{10}) + iT_2(\rho_{21}-\rho_{12}) + iT_3(\rho_{31}-\rho_{13}) - (\Gamma_{10}+r)\rho_{11} + r\rho_{00},\\
\dot{\rho}_{22} &= iT_2(\rho_{12}-\rho_{21}) - \Gamma_{20}\rho_{22},\\
\dot{\rho}_{33} &= iT_3(\rho_{13}-\rho_{31}) - \Gamma_{30}\rho_{33},\\
\rho_{00} &+ \rho_{11} + \rho_{22} + \rho_{33} = 1.
\end{aligned} \tag{2}$$

here the detunings are defined as $\delta_p = \omega_{01} - \omega_c$, $\delta_2 = \delta_p + 2\omega_{21}$, $\delta_3 = \delta_p + 2\omega_{31}$, where ω_{21}, ω_{31} are the transition frequency between $|1\rangle \rightarrow |2\rangle$ and $|1\rangle \rightarrow |3\rangle$, respectively.

The term r represents the incoherent pumping rate. The radiative decay rate of populations from $|1\rangle \rightarrow |0\rangle \rightarrow |2\rangle \rightarrow |0\rangle$ and $|3\rangle \rightarrow |0\rangle$ are Γ_{10}, Γ_{20} and Γ_{30}. In addition, γ_1, γ_2, γ_3 shows the pure dephasing rates. Thus the coherence decay rate γ_{mn} between level m to level n can be obtained by $\gamma_{0n} = \gamma_{n0} = 1/2(\Gamma_{n0} + \gamma_n)$, $(n = 1, 2, 3)$ and $\gamma_{mn} = \gamma_{nm} = 1/2(\Gamma_{m0} + \Gamma_{n0} + \gamma_m + \gamma_n)$, $(m \neq n, m, n = 1, 2, 3)$.

Now, in order to study the optical bistability behavior of the QD medium, we put the ensemble of N homogenously QD sample in a unidirectional ring cavity as shown in Fig. 1(c). The intensity reflection and transmission coefficients of mirrors 1 and 2 are R and T (with $R + T = 1$), respectively. For the sake of simplicity, we assume both mirrors 3 and 4 are perfect reflectors. The total electromagnetic field induced by N homogenously QD molecule contained in a cell of length L can be calculated as:

$$E = E_p e^{i\omega_{01}t} + C.C \tag{3}$$

Since the probe field circulates in the ring cavity, the dynamics of the probe field in the optical cavity can be governed under slowly varying envelope approximation by Maxwell's equation as

$$\frac{\partial E_p}{\partial t} + c\frac{\partial E_p}{\partial z} = \frac{i\omega_p}{2\varepsilon_0}P(\omega_p) \tag{4}$$

where c and ε_0 are the speed of light and permittivity of free space, respectively. $P(\omega_p)$ is the slowly oscillating term of the induced

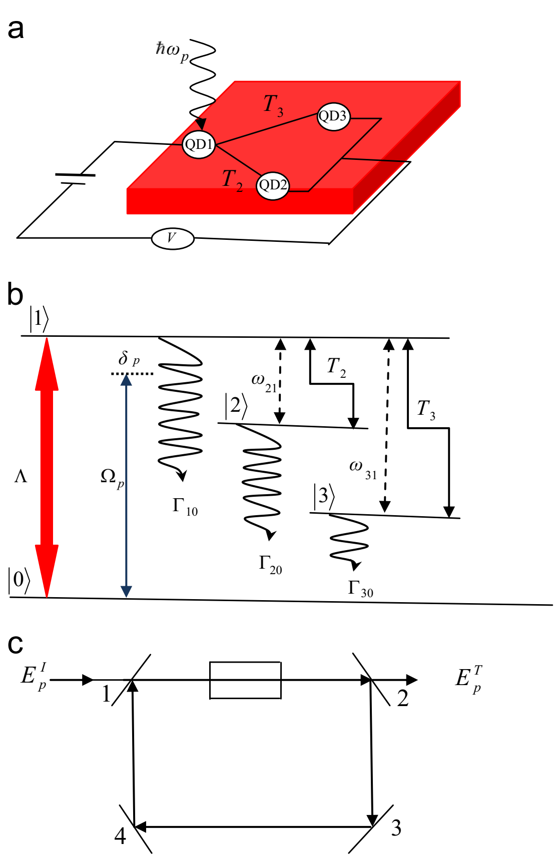

Fig. 1. (a) Schematic of the setup of the TQDs (QD1, QD2 and QD3). An optical pulse transmits the QD 1. V is a bias voltage. (b) Schematic band structure and level configuration. (c) Unidirectional ring cavity with QD sample of length L. E_P^I and E_P^T are the incident and transmitted fields, respectively. For mirrors 1 and 2 we have $R + T = 1$. Mirrors 3 and 4 are perfect reflectors.