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Manipulation of tunneling induced transparency windows and optical switching features in fivefold quantum dot molecules

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HIGHLIGHTS

- Optical properties of the multiple QDMs composed of five quantum dots are explored.
- Results show that at least one and at most four TIT windows can be established.
- The required switching time for the gain to absorption estimated approximately to be 20.7 ns.

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ABSTRACT

Transient and steady-state behavior of the probe absorption in a multiple quantum dot (QD) molecule composed of five quantum dots molecules (with a center dot and four satellite dots) is explored with application in all-optical switching. We find that the absorption spectra of the light pulse can be efficiently modified via the effect of inter-dot tunnel couplings of QDs and incoherent pumping field. Results show that depending on the values of system parameters, at least one and at most four tunneling induced transparency (TIT) windows can be established in the multiple QD medium. We then investigate the dynamical behavior of the probe absorption-amplification as well as the optical switching in pulsed regime. By adjusting the incoherent pumping rate, the required switching time for changing the gain to the absorption or vice versa is then estimated approximately to be 20.7 nanosecond (ns), that is an appropriate time for such a QDM-based switch.

1. Introduction

One of the most typically important applications of the quantum coherence and interference is electromagnetically induced transparency (EIT) [1,2]. Generally, EIT deals with the elimination of the probe absorption in atomic coherence media dressed by a strong driven field. It is feasible greatly through EIT techniques to slow down the optical pulse for slow light [3–5]. The EIT can lead to many kinds of quantum optical phenomena such as lasing without inversion [6,7], optical soliton [8,9], light storage [10], giant Kerr nonlinearity [10–13], multi-wave mixing [14–17], controlling optical bi/multistability [18–22] and so on. Besides atomic systems, theoretical and experimental studies on optical properties of semiconductor quantum wells (QWs) and quantum dots (QDs) [23–31] have become an interesting topic in the recent years. Being easily controllable in size and in the energy levels spacing, quantum dot molecules 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 [29,30,32–41]. For instance, Cheng et al. [33] have studied the quantum interference and Rabi oscillation of a V-type three-level system with two orthogonal sub-states in an elongated semiconductor quantum dot. Numerical calculations from the optical Bloch equations in their study reveal that the quantum interference in the system is enhanced with the increasing of the energy decay or splitting. Li et al. [38] 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. Coherent control of the electron tunneling in an asymmetric double QD system was investigated by Villas-Boas et al. [40].

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The dynamical evolution of the weak probe field via quantum interference is also widely studied in many literatures [42–51]. For instance, Zhang et al. compared the steady and transient optical responses of a four-level system and a three-level system, dressed by two and three laser fields, respectively [43]. Recently, the steady-state and the transient behavior of the absorption and the dispersion of a probe pulse through a triple quantum dots molecule are investigated [42].

In this paper, a multiple quantum dot molecule composed of five quantum dots is introduced. The effect of system parameters such as inter-dot tunnel coupling of QDs as well as incoherent pumping on absorption and transmission properties of probe field is investigated. It is shown that the probe absorption can be efficiently controlled, so that the number and the width of transparency windows can be engineered. Because of the critical role of tunneling in the appearance of transparency in this multiple QD, it is worth to call this effect tunneling induced transparency (TIT) [52]. We expand our discussion to the transient regime. The effect of the tunneling coupling and the rate of incoherent pumping on the dynamical behavior of the probe absorption are studied. In particular, the dynamical response of the solid system is investigated to explore the required switching time when probe absorption converts to probe gain or vice versa. For a realistic case, we reach to a switching time equal to 20.7 ns that is an appropriate time for such a QDM-based switch.

2. Model and equations of the motion

The system under consideration is a quantum dot molecule that crystallizes with a center dot and four satellite dots. Experimentally the coupling system of quantum dots is created and grown by self-assembly that are defect free and provide good electrical and optical properties. In this type of growth, the lateral quantum dot molecules are closely packed quantum dots in the growth plane. Therefore, they are potential candidates for nanoelectronic applications, because of their potential in obtaining four or five quantum dots arranged in a rectangular pattern [53]. Lateral quantum dot molecules can be realized by several growth techniques. The thin-capping-and-regrowth molecular beam epitaxial process, which can be used to obtain quantum dot molecules in one continuous growth has been demonstrated [54]. The dots number of quantum dot molecules grown can be controlled by varying the capping temperature and the capping thickness by thin-capping-and-regrowth molecular beam epitaxy (MBE) process [55]. A quantum dot molecule with four to five dots per molecule can be grown with GaAs capping thickness and InAs regrowth thickness of 25 mL and 1.5 mL respectively [56]. The schematic of the setup and detailed band structure and energy level of five tunnel-coupled QDs, which consists of five dots (QD1, QD1, QD3, QD4, and QD5) with different band structures coupled by the electron tunneling, are depicted in Fig. 1. Here T_2, T_3, T_4 and T_5 are corresponding inter-dot tunneling coupling. At nanoscale interdot separation, the hole states are localized in the QD and the electron states are rather delocalized. In the absence of optical excitation, there are no excitons 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, QD3, QD4 and QD5 forming the indirect excitons, which is denoted here as states $|2\rangle$, $|3\rangle$, $|4\rangle$ and $|5\rangle$. By placing a gate electrode between the neighboring dots, the tunnel barrier in five QDs can be controlled. In the interaction picture, the Hamiltonian of this system in the rotating wave and dipole approximations can be given by ($\hbar = 1$).

$$H = \sum_{j=0}^{5} E_j|j\rangle\langle j| + \left[(\Omega_p e^{-i\omega_p t}|1\rangle\langle 0| + T_2|2\rangle\langle 1| + T_3|3\rangle\langle 1| + T_4|4\rangle\langle 1| + T_5|5\rangle\langle 1|) + H.C.\right] \quad (1)$$

where $E_j = \hbar\omega_j$ denotes 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 to the transition $|0\rangle \rightarrow |1\rangle$, where $\wp_{01}$, e and E indicate the associated dipole transition-matrix element, the polarization vector and the electric-field amplitude of the laser pulse, respectively.

The electron-tunneling in a barrier can be described by perturbation theory which can be given by Bardeen's approach [51]. According to the Bardeen's approach, the probability of tunneling an electron in state Ψ with energy E_ψ from the first QD to state ϕ with energy E_ϕ in the second QD, is given by Fermi's Golden Rule [57]

$$w = \frac{2\pi}{\hbar}|T_e|^2\delta(E_\psi - E_\phi). \quad (2)$$

The tunneling matrix elements can be obtained by an integral over a surface in the barrier region lying between the QDs

$$T_e = \frac{\hbar}{2m}\int_{z=z_0}\left(\phi^*\frac{\partial\psi}{\partial z} - \psi^*\frac{\partial\phi}{\partial z}\right)dS \quad (3)$$

where m is the effective mass of the electron and z_0 lies in the barrier. Applying a bias voltage V , the current is

$$I = \frac{4\pi e}{\hbar}\int_0^{eV}\rho_1(E_F - eV + \varepsilon)\rho_2(E_F + \varepsilon)|T_e|^2 d\varepsilon \quad (4)$$

This means that the current is proportional to the local density of states of each QD (ρ_1, ρ_2)

at the Fermi energy (E_F). Therefore, it is possible to tune the magnitude of coupling between two QDs, by modifying the applied bias to the molecule.

The density-matrix approach is used for obtaining the dynamical behavior of the above QD system.

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] \quad (5)$$

where H describes the interaction Hamiltonian of the system.

Expanding Eq. (2) and after moving to an appropriate rotating wave, we can arrive to the density matrix equations of motion:

$$\dot{\rho}_{10} = -(i\delta_p + \gamma_{01} + \Lambda)\rho_{10} + i\Omega_p(\rho_{11} - \rho_{00}) + iT_2\rho_{20} + iT_3\rho_{30} + iT_4\rho_{40} + + iT_5\rho_{50},$$

$$\dot{\rho}_{20} = -\left(\frac{i}{2}(\delta_p + \delta_2) + \gamma_{02} + \Lambda/2\right)\rho_{20} + iT_2\rho_{10} - i\Omega_p\rho_{21},$$

$$\dot{\rho}_{30} = -\left(\frac{i}{2}(\delta_p + \delta_3) + \gamma_{03} + \Lambda/2\right)\rho_{30} + iT_3\rho_{10} - i\Omega_p\rho_{31},$$

$$\dot{\rho}_{40} = -\left(\frac{i}{2}(\delta_p + \delta_4) + \gamma_{04} + \Lambda/2\right)\rho_{40} + iT_4\rho_{10} - i\Omega_p\rho_{41},$$

$$\dot{\rho}_{50} = -\left(\frac{i}{2}(\delta_p + \delta_5) + \gamma_{05} + \Lambda/2\right)\rho_{50} + iT_5\rho_{10} - i\Omega_p\rho_{51},$$

$$\dot{\rho}_{21} = -\left(\frac{i}{2}(\delta_2 - \delta_p) + \gamma_{12} + \Lambda/2\right)\rho_{21} + iT_2(\rho_{11} - \rho_{22}) - i\Omega_p\rho_{20} - iT_3\rho_{23} - iT_4\rho_{24} - iT_5\rho_{25},$$

$$\dot{\rho}_{31} = -\left(\frac{i}{2}(\delta_3 - \delta_p) + \gamma_{13} + \Lambda/2\right)\rho_{31} + iT_3(\rho_{11} - \rho_{33}) - i\Omega_p\rho_{30} - iT_2\rho_{32} - iT_4\rho_{34} - iT_5\rho_{35},$$

$$\dot{\rho}_{41} = -\left(\frac{i}{2}(\delta_4 - \delta_p) + \gamma_{14} + \Lambda/2\right)\rho_{41} + iT_4(\rho_{11} - \rho_{44}) - i\Omega_p\rho_{40} - iT_2\rho_{42} - iT_3\rho_{43} - iT_5\rho_{45},$$

$$\dot{\rho}_{51} = -\left(\frac{i}{2}(\delta_5 - \delta_p) + \gamma_{15} + \Lambda/2\right)\rho_{51} + iT_5(\rho_{11} - \rho_{55}) - i\Omega_p\rho_{50} - iT_2\rho_{52} - iT_3\rho_{53} - iT_4\rho_{54},$$

$$\dot{\rho}_{32} = -\left(\frac{i}{2}(\delta_3 - \delta_2) + \gamma_{23}\right)\rho_{32} + iT_3\rho_{12} - iT_2\rho_{31},$$

$$\dot{\rho}_{42} = -\left(\frac{i}{2}(\delta_4 - \delta_2) + \gamma_{24}\right)\rho_{42} + iT_4\rho_{12} - iT_2\rho_{41},$$

$$\dot{\rho}_{52} = -\left(\frac{i}{2}(\delta_5 - \delta_2) + \gamma_{25}\right)\rho_{52} + iT_5\rho_{12} - iT_2\rho_{51},$$

$$\dot{\rho}_{43} = -\left(\frac{i}{2}(\delta_4 - \delta_3) + \gamma_{34}\right)\rho_{43} + iT_4\rho_{13} - iT_3\rho_{41},$$