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Transient gain–absorption of the probe field in triple quantum dots coupled by double tunneling

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ABSTRACT

The transient gain–absorption property of the probe field in a linear triple quantum dots coupled by double tunneling is investigated. It is found that the additional tunneling can dramatically affect the transient behaviors under the transparency condition. The dependence of transient behaviors on other parameters, such as probe detuning, the pure dephasing decay rate of the quantum dots and the initial conditions of the population, are also discussed. The results can be explained by the properties of the dressed states generated by the additional tunneling. The scheme may have important application in quantum information network and communication.

1. Introduction

The phenomenon of electromagnetically induced transparency (EIT), which bases on the laser induced atomic coherence, plays an important role in the interaction between light and matter [1–3]. Possible applications of EIT include slow [4–6] and fast light [7], storage of Light [8,9] and optical quantum memory [10]. And transient properties of EIT in three-level atomic systems are widely studied [11–16], because of their potential application in an optical switch [17,18]. Moreover, transient properties in four-level atomic systems [19–21], in the atomic system with spontaneously generated coherence (SGC) effect [22–24] or near a plasmonic nanostructure [25], in quantum dots (QDs) [26] and quantum wells (QWs) [27,28] are also studied.

On the other hand, double quantum dots (DQDs) are received extensive concern nowadays. By the self assembled dot growth method, DQDs can be fabricated [29]. The experimental works show that in DQDs an external electric can control the interdot electron tunneling [30] and the exciton fine structure [31]. Meanwhile, other theoretical works of DQDs such as EIT and slow light [32–34], electron tunneling [35–37], optical bistability [38,39], narrowing of fluorescence spectrum [40] are studied. Furthermore, triple quantum dots (TQDs) have been fabricated in much experimental progress [41]. Theoretical works of TQDs, such as transmission-dispersion spectrum [42], optical switch [43], resonance fluorescence spectrum [44], Kerr nonlinearity [45], optical bistability [46] and entanglement [47] are studied.

The transient gain–absorption property in DQDs has been investigated recently [48], but to our knowledge there is no investigation on transient gain–absorption property in TQDs. In this paper, we analyze the transient gain–absorption property in TQDs under double tunneling couplings. By applying the additional tunneling, the transient gain–absorption property of the probe field can be efficiently modified. The use of additional tunneling can drive the four-level TQDs system into double Λ-type configuration, which is responsible for the corresponding results. And also the impact of other parameters on the transient behavior are investigated, such as the probe detuning, the pure dephasing decay rate of the quantum dots and the initial conditions of the population. The paper is organized as followed: in Section 2, the model and the basic equations of TQDs are given. In Section 3 the numerical results and explanations are shown. Section 4 is the

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conclusions.

2. Models and equations

We consider the TQDs consisted by three vertically (in the growth direction) stacked self-assembled InAs QDs, as shown in Fig. 1(a). The QDs are grown with thin tunnel barrier of GaAs/AlGaAs, thus the electrons can coherently tunnel between the three dots. By controlling thicknesses of the QDs, the QDs can have different optical transition energies and can be optically addressable with a resonant laser frequency. And the QDs are incorporated into a Schottky diode, so that by adjusting the voltage bias each QD is charged with a single electron.

When the voltage bias is not applied, the conduction-band electron energy levels are out of resonance, therefore, the electron tunneling between the neighbor QDs is quite weak. On the contrary, when the gate voltage is applied, the conduction-band electron energy levels are on resonance, therefore, the electron tunneling between the neighbor QDs becomes very strong. The hole tunneling is neglected due to the off-resonance of the valence-band energy levels in the latter situation.

Under the resonant coupling of a probe laser field with QD1, an electron is excited in QD1. Then with the tunneling, the electron can be transferred to QD2 and QD3. Thus the TQDs structure can be treated as a four-level system (Fig. 1(b)): the ground level $|0\rangle$, where there is no excitations in any QDs, the direct exciton level $|1\rangle$, where the electron and hole are both in the first QD, the indirect exciton level $|2\rangle$, where the electron is in the second dot and the hole remains in the first dot, and the indirect exciton level $|3\rangle$, where the electron is in the third dot and the hole remains in the first dot.

The Hamiltonian in the frame rotating with double tunneling couplings is of the form

$$H=\begin{pmatrix} 0 & -\Omega_p & 0 & 0 \\ -\Omega_p & \delta_p & -T_1 & 0 \\ 0 & -T_1 & \delta_p-\omega_{12} & -T_2 \\ 0 & 0 & -T_2 & \delta_p-\omega_{12}-\omega_{23} \end{pmatrix}. \tag{1}$$

Here $\Omega_p=\mu_{01}E_p$ is the Rabi frequency of the probe field, where E_p denotes the electric field amplitude, and $\mu_{01}=\mathbf{\mu}_{01}\cdot\mathbf{e}$ denotes the electric dipole moment of transition $|0\rangle\leftrightarrow|1\rangle$. ($\mathbf{e}$ is the polarization vector.) And $\delta_p=\omega_{10}-\omega_p$ is the detuning of the probe field, with ω_p being the frequency of the probe field and ω_{10} being the frequency of the transition $|1\rangle\leftrightarrow|0\rangle$. T_1 and T_2 are the intensities of the tunneling couplings, which depend on the intrinsic sample barrier and the external electric field. ω_{12} and ω_{23} are the energy splittings of the excited states, which depend on the effective confinement potential. And we should mention that, in experiments the confined Stark effect induced by the external electric field will shift the energy levels of each dot, therefore, there is a slight external electric field dependence on the parameters ω_{12} and ω_{23}. But such effect can be easily compensated during system characterization [35].

The dynamics of the system is described by Liouville–von Neumman–Lindblad equation

$$\frac{d\rho}{dt}=-\frac{i}{\hbar}\left[H,\rho(t)\right]+L(\rho). \tag{2}$$

Here $\rho(t)$ is the density-matrix operator. The Liouville operator $L(\rho)$ describes the dissipative process. With the Markovianapproximation, Liouville operator can be written as

$$L(\rho)=\frac{1}{2}\sum_i \Gamma_{ij}(2|j\rangle\langle i|\rho|i\rangle\langle j|-\rho|i\rangle\langle i|-|i\rangle\langle i|\rho) + \gamma_{i0}^{d}(2|i\rangle\langle i|\rho|i\rangle\langle i|-\rho|i\rangle\langle i|-|i\rangle\langle i|\rho), \tag{3}$$

where the first term describes the spontaneous decay process $|i\rangle\to|j\rangle$ and the second term is the pure dephasing with rate γ_{i0}^{d}.

Substituting Eqs. (1) and (3) into Eq. (2), then the dynamics of the system is described by the following density matrix equations:

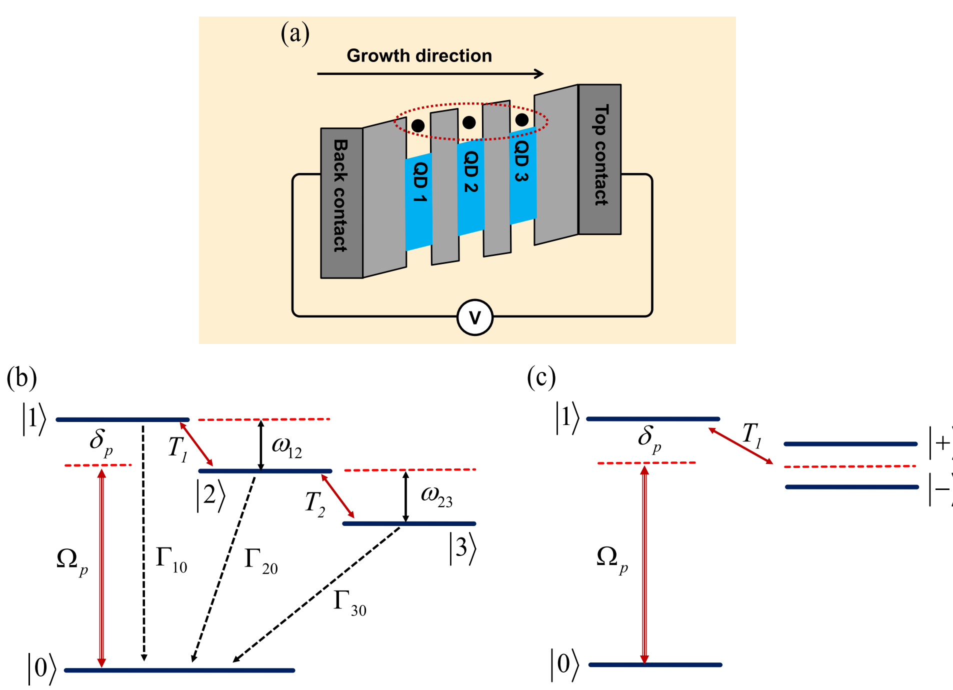

Fig. 1. (a) The schematic energy diagram of the TQDs system. (b) The schematic of the level configuration of a TQD system. (c) The partially dressed state of the TQD system under the tunneling T_2.