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Control of indirect exciton population in an asymmetric quantum dot molecule

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ABSTRACT

We analyze the problem of coherent population transfer to the indirect exciton state in an asymmetric double semiconductor quantum dot molecule that interacts with an external electromagnetic field. Using the controlled rotation method, we obtain analytical solutions of the time-dependent Schrödinger equation and determine closed-form conditions for the parameters of the applied field and the quantum system that lead to complete population transfer to the indirect exciton state, in the absence of decay effects. Then, by numerical solution of the relevant density matrix equations we study the influence of decay mechanisms to the efficiency of population transfer.

1. Introduction

The coherent control of the population dynamics of an asymmetric double semiconductor quantum dot molecule that interacts with a strong electromagnetic field has attracted some attention in recent years [1–4]. The semiconductor nanostructure (see Fig. 1) consists of two quantum dots with different band structures coupled by tunneling. At nanoscale interdot separation the hole states are localized in the quantum dots and the electron states are rather delocalized. With the application of an electromagnetic field an electron is excited from the valence band to the conduction band of one of the quantum dots. This electron can be transferred by tunneling to the other quantum dot. The tunneling barrier can be controlled by placing a gate electrode between the two quantum dots.

Particular interest [1–3] has been given to the potential of complete or highly-efficient population transfer to the indirect exciton state, state $|2\rangle$, with an electron and a hole in different quantum dots, see Fig. 2. In addition, other novel coherent nonlinear optical phenomena have been studied in the asymmetric double quantum dot molecule, such as tunneling induced transparency and slow light [5,6], transient gain without inversion [7], as well as optical pulse storage and retrieval [8,9]. Moreover, the coupling of the asymmetric double quantum dot molecule with optical cavities [10–14] and plasmonic circuits [15] has led to several useful results in optoelectronics and quantum information processing, such as π phase shift of an electromagnetic field [10], electro-optical switching [11], cavity linewidth narrowing [12], controllable optical bistability [14], as well as entanglement generation and quantum information transfer [13,15].

Here, we also address the problem of coherent population transfer to the indirect exciton state in an externally controlled asymmetric double semiconductor quantum dot molecule. We use the controlled rotation method [16], which has found several applications in the optical control of dynamics in semiconductor quantum dots [17–21], in order to obtain analytical solutions of the time-dependent Schrödinger equation for the asymmetric quantum dot molecule, in the absence of decay effects. We then use these solutions to determine closed-form conditions for the parameters of the applied field and the quantum system that can lead to complete population transfer to the indirect exciton state. Furthermore, by numerical solution of the relevant density matrix equations we study the influence of decay mechanisms to the efficiency of population transfer.

The article is organized as follows. In the next section we obtain analytical solutions of the time-dependent Schrödinger equation and present specific conditions that lead to complete population transfer to the indirect exciton state. Then, in Section 3 we present results for the time evolution of the population in the quantum states of the asymmetric quantum dot molecule from the

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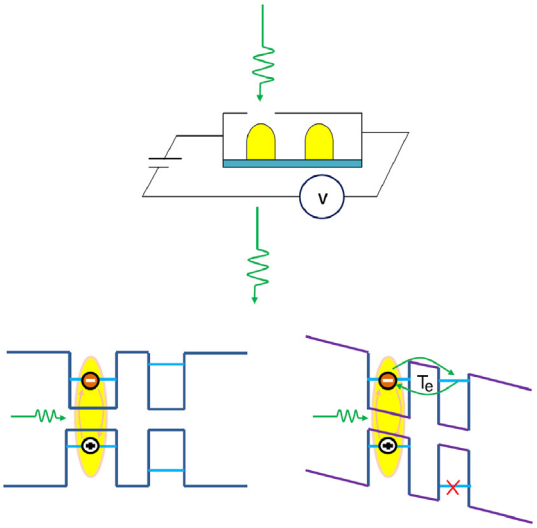

Fig. 1. (Color online.) Upper figure: Schematic of the setup. An electromagnetic field drives strongly the left quantum dot. V is a bias voltage. Lower figure: Schematic of the band structure. Lower left: without a gate voltage, electron tunneling is weak. Lower right: with applied gate voltage, conduction band levels get into resonance, increasing their coupling, while valence-band levels become even more off-resonance, resulting in effective decoupling of those levels.

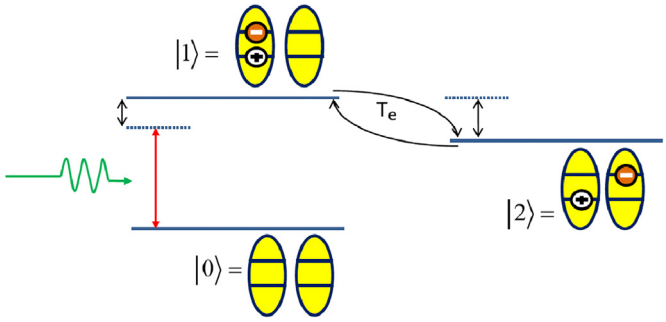

Fig. 2. (Color online.) Schematic level configuration of the double quantum dot system.

numerical solution of the density matrix equations, with or without decay effects. Finally, in Section 4 we conclude our findings.

2. Theory

The quantum dot structure under study is shown in Fig. 1. We consider an asymmetric double quantum dot structure that consists of two quantum dots with different band structures coupled by tunneling. The tunneling barrier can be controlled by placing a gate electrode between the two quantum dots [1]. In the absence of the gate voltage the conduction-band electron energy levels are out of resonance and the electron tunneling between two quantum dots is very weak. In the presence of a gate voltage the conduction-band electron levels come close to resonance and the electron tunneling between the two quantum dots is significantly enhanced [1]. In addition, in the latter case the valence-band energy levels become more off-resonant and thus the hole tunneling can be neglected.

The interaction of the quantum dot structure with an applied electromagnetic field can be described by three states, as it is shown in Fig. 2: the ground state $|0\rangle$, where the system has no excitations, the (direct) exciton state $|1\rangle$, where a pair of an electron and a hole are bound in the first quantum dot, and finally the indirect exciton state $|2\rangle$, where the hole is in the first quantum dot and the electron is in the second quantum dot.

The quantum dot structure interacts with a linearly polarized continuous wave laser field, with electric field $E(t) = E_0 \cos(\omega t)$, where E_0 is the electric field amplitude and ω the angular frequency of the electric field. The laser field couples state $|0\rangle$ with state $|1\rangle$. The Hamiltonian that describes the interaction of the electromagnetic field with the quantum system, in the dipole and rotating wave approximations, is given by

$$H = \hbar(\omega_1 - \omega_0 - \omega)|1\rangle\langle 1| + \hbar(\omega_2 - \omega_0 - \omega)|2\rangle\langle 2| + \left(\frac{\hbar\Omega}{2}|0\rangle\langle 1| + \hbar T_e|1\rangle\langle 2| + \text{H.c.}\right). \quad (1)$$

Here, $\hbar\omega_n$, with $n = 0 - 2$, is the energy of state $|n\rangle$, Ω is the Rabi frequency defined as $\Omega = -\mu E_0/\hbar$, and T_e is the electron tunneling coupling coefficient. Also, μ is the electric dipole matrix element of the transition $|0\rangle \leftrightarrow |1\rangle$.

We choose the angular frequency of the applied electromagnetic field to be $\omega = \omega_2 - \omega_0$. Then, Eq. (1) reduces to

$$H = \hbar\omega_{12}|1\rangle\langle 1| + \left(\frac{\hbar\Omega}{2}|0\rangle\langle 1| + \hbar T_e|1\rangle\langle 2| + \text{H.c.}\right), \quad (2)$$

where $\omega_{12} = \omega_1 - \omega_2$. In order to study only the coherent evolution of the system we will initially omit any decay effects and use the time-dependent Schrödinger equation for the analysis of the dynamics of the quantum system. The influence of decay effects will be considered later in the paper. We choose the time-dependent wavevector as $|\psi(t)\rangle = \sum_{n=0}^{2} b_n(t)|n\rangle$ and obtain from the time-dependent Schrödinger equation:

$$i\begin{pmatrix}\dot{b}_0(t)\\ \dot{b}_1(t)\\ \dot{b}_2(t)\end{pmatrix} = \begin{pmatrix}0 & \Omega/2 & 0\\ \Omega/2 & \omega_{12} & T_e\\ 0 & T_e & 0\end{pmatrix}\begin{pmatrix}b_0(t)\\ b_1(t)\\ b_2(t)\end{pmatrix}, \quad (3)$$

where $\dot{}$ denotes time derivative.

We will present a scheme for the solution of Eq. (3) [16]. For simplicity we assume that Ω and T_e are real and positive. We define

$$\Omega = \lambda\cos\phi, \qquad T_e = \frac{\lambda}{2}\sin\phi, \quad (4)$$

and

$$A(t) = \cos\phi b_0(t) + \sin\phi b_2(t), \quad (5)$$

$$B(t) = -\sin\phi b_0(t) + \cos\phi b_2(t). \quad (6)$$

The new set of probability amplitudes obey the differential equations

$$i\dot{A}(t) = \frac{\lambda}{2}b_1(t), \quad (7)$$

$$i\dot{b}_1(t) = \frac{\lambda}{2}A(t) + \omega_{12}b_1(t), \quad (8)$$

$$\dot{B}(t) = 0. \quad (9)$$

Eqs. (7) and (8) describe the coherent interaction of a two-level system with an external electromagnetic field in the rotating wave approximation. For the initial condition, at $t = 0$, we take the quantum dot system to be in the ground state $|0\rangle$, i.e. $b_0(0) = 1$ and $b_1(0) = b_2(0) = 0$.

In the case that $b_1(0) = 0$ the analytical solution of these equations can be written as

$$A(t) = \alpha(t)A(0), \qquad B(t) = B(0), \qquad b_1(t) = \beta(t)A(0), \quad (10)$$

where $\alpha(t)$ and $\beta(t)$ obey the equation $|\alpha|^2 + |\beta|^2 = 1$ and will be defined below. As $A(0) = \cos\phi$ and $B(0) = -\sin\phi$, we obtain the