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Enhanced index without absorption in a semiconductor quantum-dot nanostructure

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HIGHLIGHTS

- High refractive index without absorption in a solid is investigated.
- Our system is much more practical than the atomic counterpart.
- The refractive index can be easily controlled via corresponding parameters.

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ABSTRACT

We investigate the absorptive–dispersive properties of a weak field in a coupled semiconductor double-quantum-dot nanostructure. It is found that the enhanced index of refraction without absorption can be easily controlled via adjusting properly the corresponding parameters of the system. Our scheme opens the possibility to control index of refraction without absorption in a coupled semiconductor double-quantum-dot nanostructure.

1. Introduction

Quantum coherence, which plays an essential role in quantum optics, has been manifested in various branches of physics. In atomic, molecular, and optical physics, many phenomena subject to quantum coherence have been of considerable interest for many years. Examples [1–7] are electromagnetically induced transparency, highly efficient four-wave mixing, giant Kerr nonlinearity, ultraslow optical soliton, enhancement of the refractive index, and so on. On the other hand, many kinds of nonlinear quantum optical phenomena based on the quantum interference in the semiconductor quantum wells and quantum dots have also been extensively studied in recent years, such as electromagnetically induced transparency [8], enhanced index of refraction [9], ultrafast all optical switching [10], Kerr nonlinearity [11] and other novel phenomena [12–18].

In this work, we investigate the quantum-interference effect on the refractive property in a coupled semiconductor double-quantum-dot nanostructure. It is found that the refractive properties can be significantly improved via the intensity and the frequency detuning of the coupling field as well as the relative phase. Our study and the system are mainly based on Refs. [7,9], but our results are drastically different from those works. First, we are interested in studying the controllability of the refractive properties in a coupled semiconductor double-quantum-dot nanostructure. Second, a very important advantage of our scheme is that our system is much more practical than its atomic counterpart [7] due to its flexible design, controllable quantum-interference effect and wide adjustable parameters. Third, we find that the positive or negative refractive index with vanishing absorption can be easily obtained in this semiconductor double-quantum-dot nanostructure, and the switch between positive refractive index and negative refractive index just by tuning the relative phase.

2. The model and dynamic equations

We consider a coupled semiconductor double-quantum-dot nanostructure as shown in Fig. 1, where each dot has only two bound-state energy states. The quantum dots are designed to be widely separated. Thus, the lower energy states $|1\rangle$ and $|2\rangle$ are

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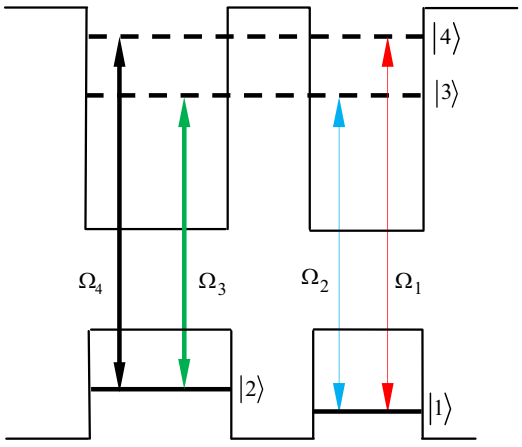

Fig. 1. Schematic diagram of the coupled semiconductor double-quantum-dot nanostructure under study.

essentially localized in the corresponding dots, as the tunneling of an electron through the potential barrier between these energy states is impossible. However, the upper energy states $|3\rangle$ and $|4\rangle$ are chosen to occur near the edge of the potential barrier separating the QDs, therefore the matrix element of electron tunneling between these two states $|3\rangle$ and $|4\rangle$ is significantly large, which leads to their strong hybridization, i.e., to the formation of two delocalized states extended between the dots. Four laser components $E_m e^{-i(\omega_m t+\phi_m)}+c.c.(m=1\text{–}4)$ are applied to the transitions $|1\rangle\leftrightarrow|3\rangle$, $|1\rangle\leftrightarrow|4\rangle$, $|2\rangle\leftrightarrow|3\rangle$ and $|2\rangle\leftrightarrow|4\rangle$, respectively, where E_m, ω_m, ϕ_m are the amplitudes, the frequencies and the initial phases. The four fields have the frequency matching relation $\omega_1+\omega_3=\omega_2+\omega_4$. E_2 is a probe field, while E_1, E_3 and E_4 are the three coupling fields. Then, in the interaction picture and under the rotating-wave approximation, the Hamiltonian of this system is given as follows ($\hbar=1$) :

$$H_{int}=(\Delta_3-\Delta_2)|2\rangle\langle 2|-\Delta_2|3\rangle\langle 3|-\Delta_1|4\rangle\langle 4| -(\Omega_1|4\rangle\langle 1|+\Omega_2|3\rangle\langle 1|+\Omega_3|3\rangle\langle 2|+\Omega_4 e^{-i\Phi}|4\rangle\langle 2|+H.c.), \quad (1)$$

where $\Delta_1=\omega_1-\omega_{41}$, $\Delta_2=\omega_2-\omega_{31}$, $\Delta_3=\omega_3-\omega_{32}$, and $\Delta_4=\omega_4-\omega_{42}$, are the frequency detunings, and ω_{41}, ω_{42}, ω_{32} and ω_{31} are resonant frequencies which associates with the corresponding transitions. These detunings satisfy the relation $\Delta_1+\Delta_3=\Delta_2+\Delta_4$. $2\Omega_1=E_1\mu_{41}/\hbar$, $2\Omega_2=E_2\mu_{31}/\hbar$, $2\Omega_3=E_3\mu_{32}/\hbar$ and $2\Omega_4=E_2\mu_{42}/\hbar$ are the Rabi frequencies of the optical fields with μ_{mn} $(m=3,4;n=1,2)$ are the dipole matrix elements. $\Phi=\phi_1+\phi_3-\phi_2-\phi_4$ is the collective phase of the four applied fields.

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

$$\frac{\partial\rho}{\partial t}=-\frac{i}{\hbar}[H,\rho(t)]+L(\rho), \quad (2)$$

being $\rho(t)$ the density matrix operator and $L(\rho)$ represents the Liouville operator that describes the decoherence process. Then we have

$$\frac{\partial\rho_{22}}{\partial t}=-\gamma_{21}\rho_{22}+\gamma_{31}\rho_{33}+\gamma_{41}\rho_{44}+i\Omega_3\rho_{32}-i\Omega_3\rho_{23} +i\Omega_4\rho_{42}e^{i\Phi}-i\Omega_4\rho_{24}e^{-i\Phi}, \quad (3)$$

$$\frac{\partial\rho_{33}}{\partial t}=-\gamma_3\rho_{33}-i\Omega_2\rho_{31}+i\Omega_2\rho_{13}-i\Omega_3\rho_{32}+i\Omega_3\rho_{23}, \quad (4)$$

$$\frac{\partial\rho_{44}}{\partial t}=-\gamma_4\rho_{44}-i\Omega_1\rho_{41}+i\Omega_1\rho_{14}-i\Omega_4\rho_{42}e^{i\Phi}+i\Omega_4\rho_{24}e^{-i\Phi}, \quad (5)$$

$$\frac{\partial\rho_{12}}{\partial t}=-\frac{\Gamma_{12}}{2}-i(\Delta_2-\Delta_3)\rho_{12}-i\Omega_3\rho_{13}+i\Omega_2\rho_{32}-i\Omega_4\rho_{14}e^{-i\Phi}+i\Omega_1\rho_{42}, \quad (6)$$

$$\frac{\partial\rho_{13}}{\partial t}=-\left(\frac{\Gamma_{13}}{2}+i\Delta_2\right)\rho_{13}-i\Omega_2(\rho_{11}-\rho_{33})-i\Omega_3\rho_{12}+i\Omega_1\rho_{43}, \quad (7)$$

$$\frac{\partial\rho_{14}}{\partial t}=-\left(\frac{\Gamma_{14}}{2}+i\Delta_1\right)\rho_{14}-i\Omega_1(\rho_{11}-\rho_{44})-i\Omega_4\rho_{12}e^{i\Phi}+i\Omega_2\rho_{34}, \quad (8)$$

$$\frac{\partial\rho_{23}}{\partial t}=-\left(\frac{\Gamma_{23}}{2}+i\Delta_3\right)\rho_{23}-i\Omega_3(\rho_{22}-\rho_{33})-i\Omega_2\rho_{21}+i\Omega_4\rho_{43}e^{i\Phi}, \quad (9)$$

$$\frac{\partial\rho_{24}}{\partial t}=-\left(\frac{\Gamma_{24}}{2}+i\Delta_4\right)\rho_{24}-i\Omega_4(\rho_{22}-\rho_{44})e^{i\Phi}-i\Omega_1\rho_{21}+i\Omega_3\rho_{34}, \quad (10)$$

$$\frac{\partial\rho_{34}}{\partial t}=-\left[\frac{\Gamma_{34}}{2}+i(\Delta_1-\Delta_2)\right]\rho_{34}-i\Omega_1\rho_{31}+i\Omega_2\rho_{14}-i\Omega_4\rho_{32}e^{i\Phi}+i\Omega_3\rho_{24}, \quad (11)$$

where $\gamma_3=\gamma_{31}+\gamma_{32}$ and $\gamma_4=\gamma_{41}+\gamma_{42}$. γ_{mn} and Γ_{mn} are lifetime broadening and dephasing broadening linewidths, respectively, and have been added phenomenologically in the above density matrix equations. Usually, Γ_{mn} is the dominant mechanism, which can be controlled by adjusting barrier thickness in coupled QDs for interband/intersubband transitions. In the following numerical calculations, we choose the parameters γ_{mn} and Γ_{mn} as $\gamma_{21}=0.0005$ meV, $\gamma_{31}=0.05$ meV, $\gamma_{32}=0.05$ meV, $\gamma_{41}=0.05$ meV, $\gamma_{42}=0.05$ meV, $\Gamma_{12}=0.001$ meV, $\Gamma_{13}=0.25$ meV, $\Gamma_{14}=0.25$ meV, $\Gamma_{23}=0.25$ meV, $\Gamma_{24}=0.25$ meV, and $\Gamma_{34}=0.3$ meV, and the choices of them are based on experimental results from Ref. [18].

3. Numerical results

As is well known, the indexes of refraction and absorption for the probe field are governed by the real and imaginary parts of the complex polarization ρ_{31} [8,9], which can be obtained from Eqs. (3) to (11). In the following, we present a few numerical results under various parametric conditions in order to demonstrate controllability of the refractive and absorptive properties for the probe field, as shown in Figs. 2–4.

In Fig. 2, we present $\mathrm{Re}(\rho_{31})$ (the solid curve represents index of refraction) and $\mathrm{Im}(\rho_{31})$ (the dashed curve represents absorption) versus probe detuning Δ_2 with parameters are $\Delta_1=\Delta_3=0$, $\Omega_2=0.1$ meV, $\Omega_3=\Omega_4=1$ meV, and $\Phi=0$. In Fig. 2a, we take a small Rabi frequency of the coupling field $\Omega_1=0.1$ meV, it is easy to see that index of refraction with zero absorption cannot be obtained. As we increase the coupling field Ω_1 to 0.2 meV (Fig. 2b), we can easily see that index of refraction with zero absorption is located at points A_1 and B_1. When the coupling field is adjusted to $\Omega_1=0.4$ meV, as shown in Fig. 2c, the maximal value of refractive index becomes large (points A_2 and B_2). This means that one can enhance the refractive index via adjusting the intensity of the coupling field E_1. However, on the condition of $\Omega_1=1$ meV (Fig. 2d), the maximal value of refractive index (the points A_3 and B_3 in Fig. 2d) becomes small in comparison with the situation in Fig. 2c, which implies that too strong coupling field E_1 will bring a destructive effect to index of refraction with zero absorption.

The appearance of the closed-loop configuration makes this system becomes quite sensitive to phases of the three coherent fields, so we show the influence of the relative phase Φ on the index of refraction in Fig. 3. As can be seen, when $\Phi=\pi/4$