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Tunneling Control of Optical Properties of a Quantum Well from Adjacent Quantum Well by Coherent Population Trapping Effect

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The coherent population trapping effect in double tunnel-coupled quantum wells is analyzed. One of two quantum wells interacts with the two-frequency laser radiation and low-frequency field, thus forming a closed contour of excitation. It is possible to control the excited level population in such a scheme of excitation by changing relative phases of the fields in the coherent population trapping state. The quantum well is bound to the other quantum well by tunnel coupling of the excited levels, therefore the population and optical properties of the other quantum well depend on the coherent population trapping state in the first quantum well and can be controlled.

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1. Introduction

At present the coherent population trapping (CPT) effect attracts a considerable attention of researchers. The essence of this effect is the appearance of a specific superposition of long-lived states in a multilevel quantum system that interacts with a two-frequency coherent (typically, laser) field [1]. This superposition state (dark state) does not interact with the field. Dark resonances were investigated theoretically [2] and experimentally in semiconductor quantum wells based on InGaAs/AlInAs [3] and GaAs [4]. Dark resonances are particularly promising for the development of devices for recording and storing quantum information [5] and also for quantum logic elements [6]. The methods of recording and reading of qubits with a high degree of fidelity were realized on the basis of the CPT resonance in the atoms inside an optical lattice.

2. Level system and mathematical model

The goal of our work was to study dark resonances in semiconductor double tunnel-coupled quantum wells (Fig. 1).

2.1. Excited states in the conduction band

Excited resonant states in the conduction band split into two levels $|4\rangle$ and $|5\rangle$ due to tunnel coupling (the barrier between the wells is permeable). States $|4\rangle$ and $|5\rangle$ have wave functions which are symmetric and antisymmetric combinations of the wave function in a single quantum well.

2.2. Ground states in the valence band

We consider two sublevels $|1\rangle$ and $|2\rangle$ in the left quantum well and one sublevel $|3\rangle$ in the right quantum well. Level $|3\rangle$ is not in resonance with levels $|1\rangle$ and $|2\rangle$, and therefore tunneling through the barrier in the valence band is hindered. Nevertheless, mixing of populations between lower levels does occur because of imperfection of well boundaries and level broadening ($\gamma_{ij}, i, j = 1, 2, 3$ in Fig. 1).

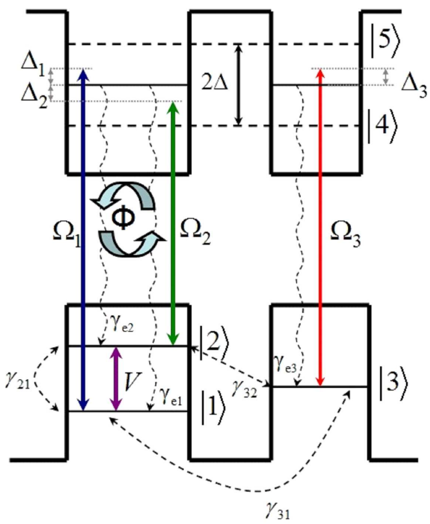

Fig. 1. Structure consisting of double tunnel-coupled quantum wells. Here $\Delta_{1,2,3}$ are laser detunings of optical fields, $\Omega_{1,2,3}$ are Rabi frequencies of optical fields and V is the Rabi frequency of infrared field, 2Δ is tunneling splitting, Φ is the relative phase of fields Ω_1, Ω_2 and V in the left QW.

2.3. Interaction with electromagnetic field

States $|1\rangle$, $|2\rangle$ and $|4\rangle$ ($|5\rangle$) are bound by electromagnetic fields with the Rabi frequencies Ω_1, Ω_2, V and constitute a system with a closed contour of excitation. It is important to take into account the initial phases φ_i ($i = 1, 2, lf$) of these fields. The CPT state in such a system can be controlled by changing the relative phase

$\Phi = \varphi_1 - \varphi_2 - \varphi_{lf}$ [7]. The $|3\rangle \longrightarrow |4\rangle\,(|5\rangle)$ transition is the additional excitation channel. A spontaneous decay of the excited states that takes place in this structure is shown as γ_{ei} in Fig. 1.

The population dynamics in the QW can be described by the density matrix equation

$$\frac{\partial \rho_{ik}}{\partial t} = -\frac{\mathrm{i}}{\hbar}\sum_l \left[H_{il}\rho_{lk} - \rho_{il}H_{lk}\right] + \sum_{l,m} \Gamma_{ik,lm}\rho_{lm}, \quad (1)$$

where H is the Hamiltonian, Γ is the relaxation matrix, and ρ_{ij} is the density matrix. The Hamiltonian H can be presented as $H = H_0 + H_{\text{int}}$, where H_0 is the Hamiltonian in the absence of a laser field

$$H_0 = \sum_{i=1}^{5} \varepsilon_i \,|i\rangle\,\langle i|\,, \quad (2)$$

where ε_i is the energy of the i-th level, and H_{int} describes the interaction of the quantum system with the laser field. In the resonance approximation [7]:

$$\begin{aligned} H_{\text{int}} &= \hbar\Omega_1\,\mathrm{e}^{-\mathrm{i}(\nu_1 t+\varphi_1)}(|5\rangle\,\langle 1| + k\,|4\rangle\,\langle 1|) \\ &+\hbar\Omega_2\,\mathrm{e}^{-\mathrm{i}(\nu_2 t+\varphi_2)}(|5\rangle\,\langle 2| + q\,|4\rangle\,\langle 2|) \\ &+\hbar\Omega_3\,\mathrm{e}^{-\mathrm{i}\nu_3 t}(|5\rangle\,\langle 3| + p\,|4\rangle\,\langle 3|) \\ &+\hbar V\,\mathrm{e}^{-\mathrm{i}(\nu_{lf} t+\varphi_{lf})}\,|2\rangle\,\langle 1| + \text{H.c.} \end{aligned} \quad (3)$$

where ν_i are the carrier frequencies of the electromagnetic fields, $k = d_{41}/d_{51}$, $q = d_{42}/d_{52}$, $p = d_{43}/d_{53}$ are the ratios between the matrix elements of transitions. The relaxation matrix Γ can be taken from experimental works, for example [8].

After substitution the explicit form of the Hamiltonian (3) into Eq. (1) we change the variables: $\rho_{mn} = \tilde{\rho}_{mn}\,\mathrm{e}^{\mathrm{i}(\nu_j t+\varphi_j)}$, $\rho_{nn} = \tilde{\rho}_{nn}$. It allows us to get the set of equations for the density matrix in the rotating wave approximation [9].

3. Stationary laser fields

Let us consider the steady-state case when the laser intensity is constant. Figure 2 shows the dependence of the ground state population ρ_{33} on the two-photon detuning $\delta = (\Delta_1 - \Delta_2)/2$. When the relative phase Φ of the fields in the left QW is zero, the CPT resonance takes place in the left QW, and the major part of the population is at ground levels $|1\rangle$ and $|2\rangle$ (Fig. 2, solid curve).

The ground state $|3\rangle$ in the right QW is bound with the left QW by the field Ω_3 and tunnel coupling, therefore the population ρ_{33} can be controlled by the phase Φ and has a resonance dependence on detuning δ (Fig. 2).

In Figs. 2 and 3 all parameters are given in values of the rate of spontaneous relaxation of the excited states $\gamma \approx 10^{11}$ s^{-1}.

If we change the relative phase from $\Phi = 0$ to $\Phi = \pi/2$, the dark state in the left well is destroyed and the population of level $|3\rangle$ increases (Fig. 2, dashed curve).

In contrast to the excited states, state $|3\rangle$ is long-lived, therefore the distribution of the populations of the levels

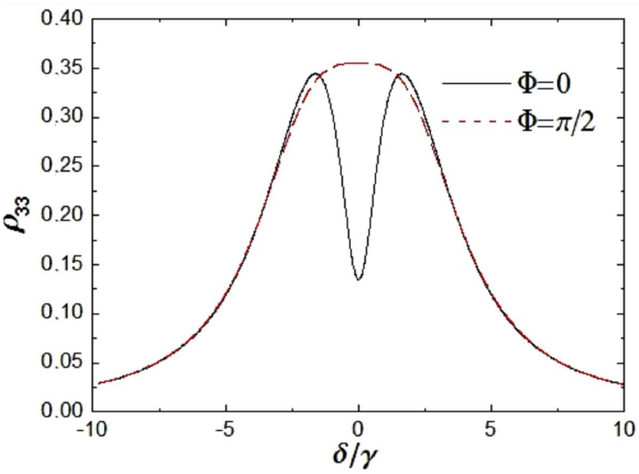

Fig. 2. Dependence of population ρ_{33} of the ground state $|3\rangle$ on two-photon detuning $\delta = (\Delta_1 - \Delta_2)/2$ for two values of relative phase Φ of the closed contour of excitation. Here $\Omega_1 = \Omega_2 = \Omega_3 = V = 2\gamma$, $\Delta = \gamma$.

in the valence band can be preserved after switching off the laser fields for the time of about $\gamma_{31}^{-1} \approx 10^{-6}$ s. This can be used for creation of the quantum memory protocol for scalable quantum communications in the solid state.

4. Pulsed laser field Ω_3

Now we consider the case when the intensities of fields Ω_1, Ω_2 and V are stationary but the field Ω_3 is pulsed and is much stronger (about 10 times) than the other fields (Fig. 3a). The Ω_3 pulse duration is about $10\gamma^{-1} \approx 0.1$ ns. The spectral width of such a pulse is $\approx 0.1\gamma$, which is less than the width of the levels in the QW. Therefore, the field Ω_3 interacts only with the $|3\rangle \leftrightarrow |4\rangle\,(|5\rangle)$ transition. Let us trace the dynamics of the population of the excited levels $\rho_{44} + \rho_{55}$ because it demonstrates us the response of the solid state medium and absorption of field Ω_3.

The population dynamics of the excited levels is shown in Fig. 3b. The curve is seen to exhibit two peaks. The stationary fields Ω_1, Ω_2 and V form a closed contour of excitation in the left QW, therefore it is possible to control the CPT resonance by changing the relative phase Φ.

In the case of $\Phi = 0$ (Fig. 3(b), dot-dashed curve) the CPT in the left QW takes place before the Ω_3 pulse. As a result, the major part of the population moves to levels $|1\rangle$ and $|2\rangle$ and remains trapped there. During the Ω_3 pulse, level $|3\rangle$ is almost empty, the structure interacts with the pulse weakly, and we see two small peaks. These peaks appear because a small part of the population is at level $|3\rangle$ before the pulse due to the stirring rate γ_{31}.

In the case of $\Phi = \pi/4$ and $\Phi = \pi/2$ (Fig. 3b, dashed and solid curves) the entire population is pumped by the Ω_1 and Ω_2 fields to level $|3\rangle$ before the Ω_3 pulse. At the beginning of the pulse the population is fully pumped to the left QW to levels $|1\rangle$ and $|2\rangle$. This gives the first peak

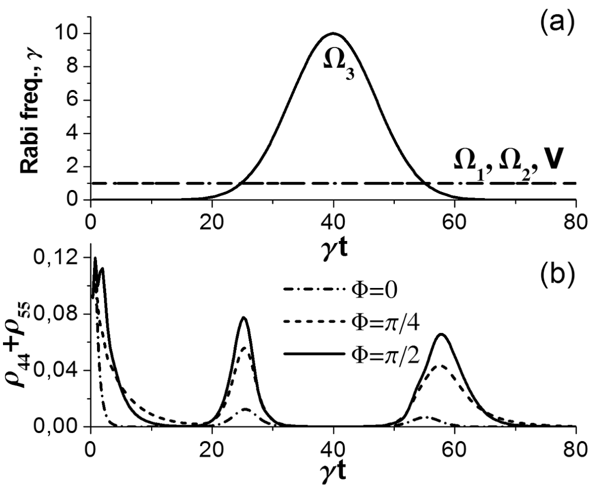

Fig. 3. (a) Dependence of Rabi frequencies of the fields interacting with the nanostructure on time. (b) Dependence of summary population $\rho_{44} + \rho_{55}$ of excited states $|4\rangle$ and $|5\rangle$ on time. Here Rabi frequencies are $\Omega_1 = \Omega_2 = V = \gamma$ and the pulse is $\Omega_3 = 10\gamma \exp\left(-\left(\frac{t-40\gamma^{-1}}{10\gamma^{-1}}\right)^2\right)$. The two-photon detuning $\delta = 0$.

in the curves. At the end of the pulse we have the reverse process, i.e., pumping of the population to the right QW. We can see this as the second peak in the curves.

5. Conclusions

Double tunnel-coupled quantum wells interacting with a multicomponent laser radiation have been investigated. The resonant curve of ground level $|3\rangle$ of the right quantum well (see Fig. 1) was obtained for the steady-state case. It has been shown that it is possible to control the population in a quantum well (QW) from an adjacent QW by changing the relative phase Φ of a closed contour of excitation. If $\Phi = 0$ and the two-photon detuning δ of fields Ω_1 and Ω_2 is zero, the coherent population trapping (CPT) resonance takes place in the left QW and the major part of the population is trapped there. If $\Phi \neq 0$, the population is pumped to the right QW. These effects can be useful for the quantum memory where qubit of information is written to the low-frequency coherence.

Temporal dynamics of the QW population for the pulsed radiation has been investigated. We considered the case of stationary fields interacting with one QW and a strong pulse of the field interacting with the other QW. Due to tunnel coupling of the QWs the temporal dynamics of the upper levels had a two-peak character. The amplitudes of these peaks can be controlled by changing the relative phase Φ of the closed excitation contour. The peak widths are several times smaller than that of the initial pulse. Thus, high harmonics of pulsed radiation can be generated and ultrashort pulses can be obtained in such a system of QWs.

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References

[1] B.D. Agapiev, M.B. Gorniy, B.G. Matisov, Yu.V. Rozhdestvensky, *UFN* **163**, 1 (1993).

[2] M. Lindberg, R. Binder, *Phys. Rev. Lett.* **75**, 1403 (1995).

[3] G.B. Serapiglia, E. Paspalakis, C. Sirtori, K.L. Vodopyanov, C.C. Phillips, *Phys. Rev. Lett.* **84**, 1022 (2000).

[4] M.C. Phillips, H. Wang, I. Rumyantsev. N.H. Kwong, R. Takayama, R. Binder, *Phys. Rev. Lett.* **91**, 183602 (2003).

[5] A. Nazarkin, R. Netz, R. Sauerbrey, *Phys. Rev. Lett.* **92**, 043002 (2004).

[6] J.H. Shapiro, F.N.C. Wong, *Phys. Rev. A* **73**, 012315 (2006).

[7] A.N. Litvinov, K.A. Barantsev, B.G. Matisov, G.A. Kazakov, Yu.V. Rozhdestvensky, *Opt. Commun.* **305**, 155 (2013).

[8] E.A. Korsunsky, N. Leinfellner, A. Huss, S. Baluschev, L. Windholz, *Phys. Rev. A* **59**, 2302 (1999).

[9] M.O. Scully, M.S. Zubairy *Quantum Optics*, Cambridge University Press, Cambridge 1997.