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Control of transient gain absorption via tunneling and incoherent pumping in triple quantum dots

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Abstract

The transient gain-absorption properties of the probe field in vertical triple quantum dots assisted by double tunneling and incoherent pumping are investigated. With a proper intensity value and detuning of the second tunneling, the transient gain in triple quantum dots with incoherent pumping can be completely eliminated. In addition, the incoherent pumping affects both the amplitude of the transient absorption and the steady-state value. The dependence of transient behaviors on other parameters, such as the radiative decay rate and the pure dephasing decay rate of the quantum dots, is also discussed. The scheme may have important applications in quantum information networks and communication.

Keywords: triple quantum dots, tunneling, transient evolution

(Some figures may appear in colour only in the online journal)

1. Introduction

Optically active quantum dots (QDs) are semiconductor nanocrystals that confine the motion of both electrons and holes in regions of space with sizes comparable to or smaller than the exciton Bohr radius. QDs have three-dimensional (3D) carrier confinement, while the holes and electrons in QDs only occupy the states with discrete energies. QDs can be integrated in solid-state devices, and devices such as diodes [1], lasers [2–4] and single photon sources [5] have been realized.

Furthermore, two or more QDs can form quantum dot molecules (QDMs) [6]. The simplest QDM system is a double quantum dot (DQD), which contains two vertically [7, 8] or laterally [9] coupled QDs. The investigation of the spectrum of lateral DQDs is in its infancy, because the fabrication of such structures requires special growth protocols. By contrast, much progress has been achieved for vertical DQDs [10–16]. It is also predicted that with a laser field an electron can be excited in one dot, and then the excited electron can tunnel to the second dot by applying an external voltage [17, 18].

The development of a growth technique for DQDs opens up the possibility of fabricating and exploiting triple quantum dots (TQDs). Previous works have shown that TQDs can be obtained by both electrostatic gates on a 2D electron gas [19–21] and self-assembled epitaxial growth [9, 22–24]. Based on the latter method, much work on TQDs has been done because such nanostructures can be conveniently studied by optical spectroscopy [25–31].

On the other hand, because transient properties have potential applications in optical switches [32, 33], the transient properties of probe fields in atomic systems [34–42] and semiconductor nanostructures [43–47] are being widely

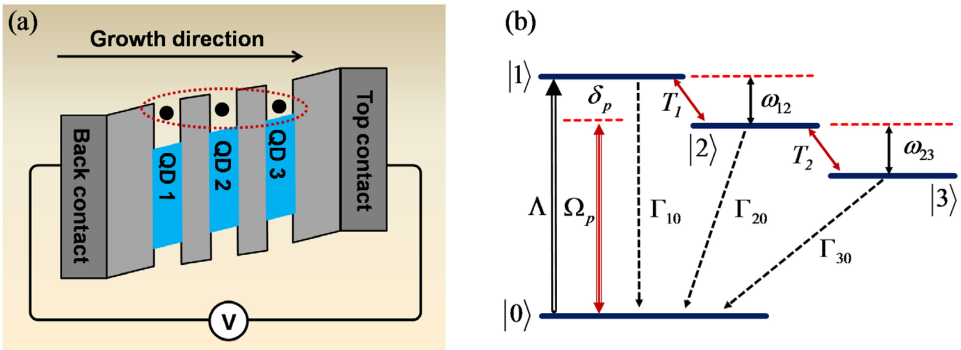

Figure 1. (a) Schematic energy diagram of the TQD system. (b) Schematic of the level configuration of a TQD system.

studied. A recent study showed that the transient properties of the probe field in DQDs exhibit periodic absorption and gain [48]. However, there has been no investigation of the transient properties in TQDs with incoherent pumping. In this paper, we theoretically investigate the transient gain-absorption properties of the probe field in vertical TQDs assisted by tunneling coupling and incoherent pumping. The probe field in TQDs with incoherent pumping can exhibit transient absorption without any gain, with a proper intensity value and detuning of the second tunneling. In addition, changing the incoherent pumping does not bring in transient gain, but it does affect both the amplitude of the transient absorption and the steady-state value. Finally, the impact of the radiative decay rate and the pure dephasing decay rate of QDs is also discussed.

2. Models and equations

Figure 1(a) shows the vertical TQDs system, which contains three vertically stacked self-assembled InAs QDs. Such QDs are incorporated into a Schottky diode, and thus each dot is charged with one electron. The electrons can tunnel between the QDs coherently due to the thin barrier of GaAs/AlGaAs and the hole tunneling can be neglected for the off-resonance of the valence-band energy levels in the latter position. The optical transition energies controlled by the thickness of the QDs can be probed with a resonant laser field. If voltage bias is applied, the conduction-band electron energy levels are resonant, leading to strong electron tunneling between the neighboring QDs. As with previous studies [29–31], the system can be treated as a four-level system (figure 1(b)) containing one ground state $|0\rangle$, one direct exciton state $|1\rangle$ and two indirect exciton states $|2\rangle$ and $|3\rangle$. The probe field probes the transition of states $|0\rangle$ and $|1\rangle$, and double tunneling couples states $|1\rangle$ and $|2\rangle$ and states $|2\rangle$ and $|3\rangle$, respectively. An incoherent pump is also considered, which can be controlled by well-known sequential tunneling processes [49].

In the frame rotation, the Hamiltonian of such a system is

$$H = \delta_p|1\rangle\langle 1| + (\delta_p - \omega_{12})|2\rangle\langle 2| + (\delta_p - \omega_{12} - \omega_{23})|3\rangle\langle 3| + \left(\Omega_p|0\rangle\langle 1| + T_1|2\rangle\langle 1| + T_2|3\rangle\langle 2| + \text{H.c.}\right). \quad (1)$$

Here $\Omega_p = \mu_{01}E_p$ and $\delta_p = \omega_{10} - \omega_p$ are the Rabi frequency and detuning of the probe field, respectively. $\mu_{01} = \boldsymbol{\mu}_{01}\cdot\mathbf{e}$ is the electric dipole moment of the transition $|0\rangle \leftrightarrow |1\rangle$, $\mathbf{e}$ is the polarization vector, E_p is the electric field amplitude, ω_p is the frequency of the probe field and ω_{10} is the frequency of the transition $|1\rangle \leftrightarrow |0\rangle$. T_1 and T_2 are the tunneling couplings, depending on the voltage bias and the intrinsic sample barrier. ω_{12} and ω_{23}, which depend on the effective confinement potential, are the tunneling detuning of states $|1\rangle$ and $|2\rangle$, and states $|2\rangle$ and $|3\rangle$, respectively.

Then the density matrix equations of such a system with incoherent pumping are

$$\dot{\rho}_{01} = \mathrm{i}\Omega_p(\rho_{11} - \rho_{00}) - \mathrm{i}T_1\rho_{02} + \left[\mathrm{i}\delta_p - \left(\frac{\Gamma_{10}}{2} + \gamma_{10}^d + \Lambda\right)\right]\rho_{01}, \quad (2a)$$

$$\dot{\rho}_{02} = \mathrm{i}\Omega_p\rho_{12} - \mathrm{i}T_1\rho_{01} - \mathrm{i}T_2\rho_{03} + \left[\mathrm{i}(\delta_p - \omega_{12}) - \left(\frac{\Gamma_{20}}{2} + \gamma_{20}^d + \frac{\Lambda}{2}\right)\right]\rho_{02}, \quad (2b)$$

$$\dot{\rho}_{03} = \mathrm{i}\Omega_p\rho_{13} - \mathrm{i}T_2\rho_{02} + \left[\mathrm{i}(\delta_p - \omega_{12} - \omega_{23}) - \left(\frac{\Gamma_{30}}{2} + \gamma_{30}^d + \frac{\Lambda}{2}\right)\right]\rho_{03}, \quad (2c)$$

$$\dot{\rho}_{11} = \mathrm{i}\Omega_p(\rho_{01} - \rho_{10}) + \mathrm{i}T_1(\rho_{21} - \rho_{12}) - (\Gamma_{10} + \Lambda)\rho_{11} + \Lambda\rho_{00}, \quad (2d)$$

$$\dot{\rho}_{12} = \mathrm{i}\Omega_p\rho_{02} + \mathrm{i}T_1(\rho_{22} - \rho_{11}) - \mathrm{i}T_2\rho_{13} - \left[\mathrm{i}\omega_{12} + \left(\frac{\Gamma_{10} + \Gamma_{20}}{2} + \gamma_{10}^d + \gamma_{20}^d + \frac{\Lambda}{2}\right)\right]\rho_{12}, \quad (2e)$$

$$\dot{\rho}_{13} = \mathrm{i}\Omega_p\rho_{03} + \mathrm{i}T_1\rho_{23} - \mathrm{i}T_2\rho_{12} - \left[\mathrm{i}(\omega_{12} + \omega_{23}) + \left(\frac{\Gamma_{10} + \Gamma_{30}}{2} + \gamma_{10}^d + \gamma_{30}^d + \frac{\Lambda}{2}\right)\right]\rho_{13}, \quad (2f)$$

$$\dot{\rho}_{22} = \mathrm{i}T_1(\rho_{12} - \rho_{21}) + \mathrm{i}T_2(\rho_{32} - \rho_{23}) - \Gamma_{20}\rho_{22}, \quad (2g)$$

$$\dot{\rho}_{23} = \mathrm{i}T_1\rho_{13} + \mathrm{i}T_2(\rho_{33} - \rho_{22}) - \left[\mathrm{i}\omega_{23} + \left(\frac{\Gamma_{20} + \Gamma_{30}}{2} + \gamma_{20}^d + \gamma_{30}^d\right)\right]\rho_{23}, \quad (2h)$$

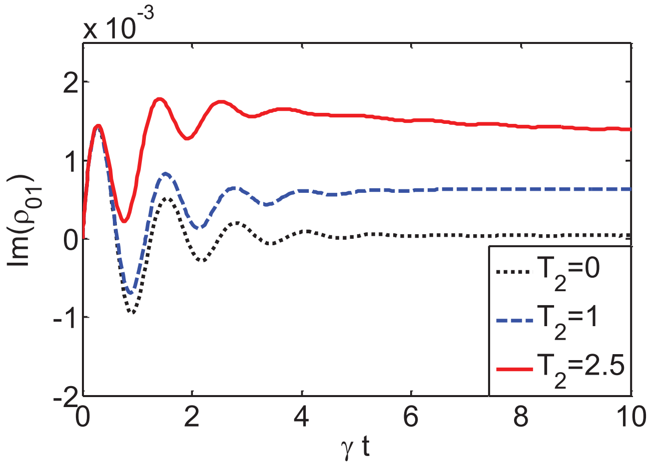

Figure 2. The time evolution of $\mathrm{Im}(\rho_{10})$ for varying tunneling intensity T_2. The initial conditions of the population are $\rho_{00}(0) = 1$ and otherwise $\rho_{ij}(0) = 0$ $(i, j = 0 - 3)$. The parameters are $\hbar\Omega_p = 0.01\gamma$, $\hbar T_1 = 2\gamma$, $\delta_p = 0$, $\omega_{12} = \omega_{23} = 0$, $\hbar\Gamma_{10} = \gamma$, $\Gamma_{20} = \Gamma_{30} = 10^{-4}\Gamma_{10}$, $\hbar\gamma_{10}^{d} = 0.5\gamma$ and $\gamma_{20}^{d} = \gamma_{30}^{d} = 10^{-3}\gamma_{10}^{d}$. All the parameters are scaled by $\gamma = 6.6\,\mu eV$.

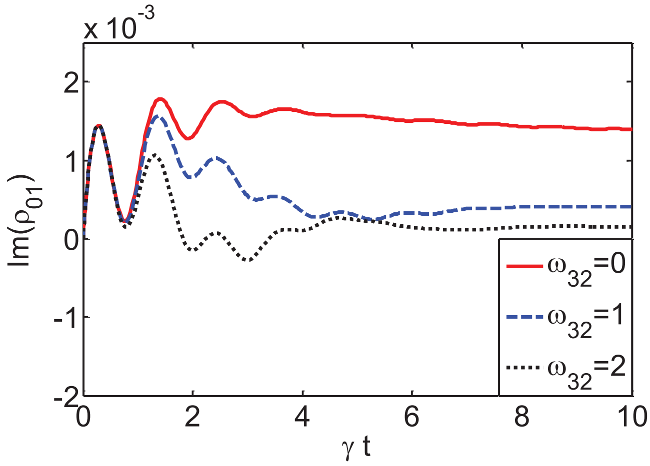

Figure 3. The time evolution of $\mathrm{Im}(\rho_{10})$ for varying tunneling detuning ω_{23}. The other parameters are the same as those used in figure 2, except that $\hbar T_2 = \gamma$.

$$\dot{\rho}_{33} = \mathrm{i}T_2(\rho_{23} - \rho_{32}) - \Gamma_{30}\rho_{33}, \qquad (2i)$$

with $\rho_{00} + \rho_{11} + \rho_{22} + \rho_{33} = 1$ and $\dot{\rho}_{ij} = \dot{\rho}_{ji}^{*}$ $(i, j = 0, 1, 2, 3)$. Γ_{i0} $(i = 1, 2, 3)$ is the radiative decay rate from level $|i\rangle$ to level $|0\rangle$, γ_{i0}^{d} $(i = 1, 2, 3)$ is the pure dephasing decay rate of the transition $|i\rangle \to |0\rangle$ and Λ is the incoherent pumping.

In the following, we will plot the time evolution of the properties of the probe field, which is determined by the imaginary part of ρ_{10}. The imaginary part of ρ_{10} can be obtained by solving equations (2*a*)–(2*i*). The parameters used in our calculation are $\hbar\Omega_p \sim 0 - 0.1\,\mu$eV, $\hbar T_1$, $\hbar T_2 \sim 10 - 100\,\mu eV$, $\hbar\omega_{12}$, $\hbar\omega_{23} \sim -30$–$30\,\mu$eV, $\hbar\Lambda \sim 0 - 10\,\mu eV$, $\hbar\Gamma_{10} \sim 0 - 6.6\,\mu eV$, $\Gamma_{20} = \Gamma_{30} = 10^{-4}\Gamma_{10}$, $\hbar\gamma_{10}^{d} \sim 0 - 6.6\,\mu$eV and $\gamma_{20}^{d} = \gamma_{30}^{d} = 10^{-3}\gamma_{10}^{d}$ [29].

3. Results and discussions

First we see the impact of the tunneling T_2 on the transient gain-absorption spectrum, and the time evolution of $\mathrm{Im}(\rho_{10})$ varying the intensity of the tunneling T_2 is shown in figure 2. Without the tunneling T_2, the system is reduced to DQDs, $\mathrm{Im}(\rho_{10})$ exhibits periodic absorption and gain, and it eventually goes to a steady-state value with very small absorption (dotted line in figure 2). Then, with the tunneling T_2, the system turns into TQDs. When the value of T_2 is not large, i.e. $T_2 = \gamma$, as can be seen from the dashed line in figure 2, the amplitude of the transient gain decreases and, starting with the second oscillation period, the transient gain is eliminated. In addition, the steady-state value of $\mathrm{Im}(\rho_{10})$ exhibits absorption with a nonzero value. As the solid line in figure 2 shows, with increasing intensity of the tunneling T_2, the transient gain vanishes within the first oscillation period. In addition, both the transient absorption values and the steady-state value increase obviously. However, with varying tunneling T_2 values, the oscillation frequency of $\mathrm{Im}(\rho_{10})$ remains almost unchanged.

Next, in figure 3 we show the impact of the tunneling detuning ω_{23} on the transient gain-absorption spectrum. With zero tunneling detuning, $\mathrm{Im}(\rho_{10})$ exhibits transient absorption over the whole process, and finally reaches a steady-state with large absorption, as shown in the solid line in figure 3. We then consider cases where the detuning of the tunneling deviates from zero. With small detuning, as the dashed line in figure 3 shows, $\mathrm{Im}(\rho_{10})$ still exhibits transient absorption without any transient gain; however, after several oscillation periods, the value of the transient absorption decreases dramatically and finally reaches a steady-state with very small absorption. When the tunneling detuning continues to increase, from the dotted line in figure 3 one can see that, beginning with the second oscillation period, transient gain shows up in the spectrum. After that, $\mathrm{Im}(\rho_{10})$ rises to a positive value again and goes smoothly to a steady-state that is close to a zero value.

From figures 2 and 3, it can be concluded that the tunneling intensity T_2 and the tunneling detuning ω_{23} have little impact on the transient oscillation frequency; however, they do have a significant impact on the transient gain-absorption behavior and steady-state value. With larger tunneling intensity and smaller tunneling detuning, the transient gain vanishes, and the steady-state absorption reaches a large value. Compared with DQDs, the most significant feature of TQDs is the fact that the transient gain can be eliminated completely with suitable parameters.

We will then see the impact of incoherence pumping on the transient gain-absorption spectrum, and show the time evolution of $\mathrm{Im}(\rho_{10})$ for different incoherence pumping Λ in figure 4. When the incoherence pumping Λ is small, $\mathrm{Im}(\rho_{10})$ always exhibits transient absorption in the process, and after several oscillation periods $\mathrm{Im}(\rho_{10})$ reaches a steady-state with large absorption, as shown in the dotted line in figure 4. Then, when the incoherence pumping is increased to 0.5γ, as shown in the solid line in figure 4, the oscillation frequency stays the same; however, the amplitude of the transient absorption decreases and it takes $\mathrm{Im}(\rho_{10})$ less time to reach a smaller steady-state value. As can be seen from the dashed line in

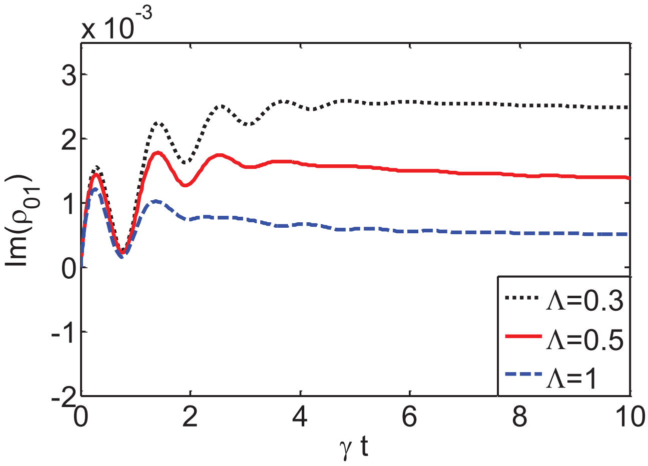

Figure 4. The time evolution of $\mathrm{Im}(\rho_{10})$ for varying incoherent pumping Λ. The other parameters are the same as those used in figure 2, except that $\hbar T_2 = \gamma$.

figure 4, with increased incoherence pumping the amplitude of the transient absorption and the steady-state value continue to decrease. However, no transient gain shows up. So it can be concluded from figure 4 that increasing the incoherence pumping Λ will not bring in transient gain, but will lead to a decreased amplitude of the transient gain and steady-state value.

In figure 5 we plot the time evolution of $\mathrm{Im}(\rho_{10})$ for varying values of γ_{10}^{d} to see the influence of the pure dephasing decay rate on transient behaviors. When $\gamma_{10}^{\mathrm{d}} = \gamma$, $\mathrm{Im}(\rho_{10})$ always exhibits transient absorption without any gain. The transient gain oscillates for several periods and then goes to a steady-state with a large absorption value, as shown in the dotted line in figure 5. Then, when γ_{10}^{d} decreases to 0.5γ, the amplitude of the transient absorption decreases, and $\mathrm{Im}(\rho_{10})$ finally reaches a smaller steady-state absorption value (solid line in figure 5). Finally, when γ_{10}^{d} goes to zero, as the dashed line in figure 5 shows, $\mathrm{Im}(\rho_{10})$ still oscillates above a zero value and exhibits absorption without any gain. In addition, both the steady-state value and the amplitude of the transient gain decrease.

Our final aim is to investigate the impact of the decay rates on the transient gain-absorption spectrum. In figure 6 we show the time evolution of $\mathrm{Im}(\rho_{10})$ for varying decay rates Γ_{10}. As can be seen from figure 6, for different values of Γ_{10}, $\mathrm{Im}(\rho_{10})$ always exhibits transient absorption without any gain. Within the first three oscillation periods, the amplitude of the transient absorption and the oscillation frequency do not change much. However, after that, the spectrum of the transient absorption begins to separate and eventfully goes to the steady-state. With a smaller Γ_{10} value, $\mathrm{Im}(\rho_{10})$ acquires a smaller steady-state value and oscillates through more periods.

So, it can be concluded from figures 5 and 6 that, once the transient gain has been eliminated by choosing suitable tunneling parameters, it will not appear even when the pure dephasing and the radiative decay rates are varied. Furthermore, with smaller γ_{10}^{d} and Γ_{10} values, $\mathrm{Im}(\rho_{10})$ will acquire a smaller steady-state value.

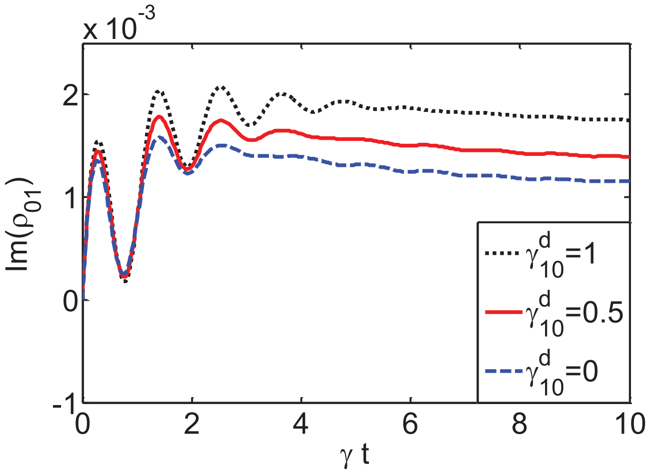

Figure 5. The time evolution of $\mathrm{Im}(\rho_{10})$ for varying pure dephasing decay rate γ_{10}^{d}. The other parameters are the same as those used in figure 2, except that $\hbar T_2 = \gamma$.

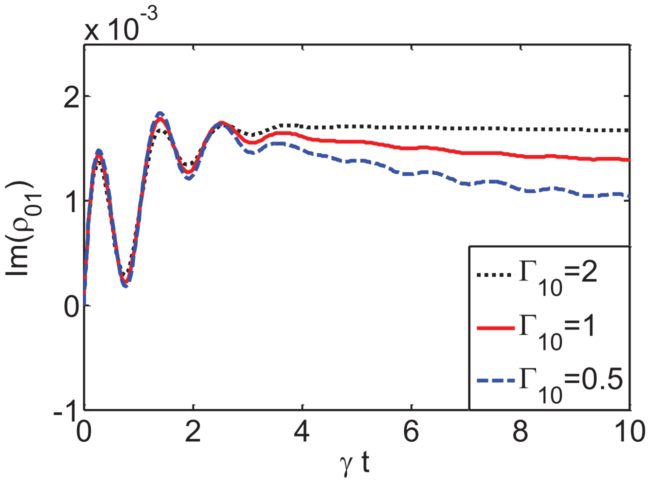

Figure 6. The time evolution of $\mathrm{Im}(\rho_{10})$ for varying decay rate Γ_{10}. The other parameters are the same as those used in figure 2, except that $\hbar T_2 = \gamma$.

4. Conclusions

In conclusion, we have theoretically investigated the transient gain-absorption properties of the probe field in vertical TQDs assisted by double tunneling and incoherent pumping. We found that with a large intensity and small detuning of the second tunneling, the transient gain in TQDs with incoherent pumping can be completely eliminated. In this situation, the increased incoherent pumping will not bring in the transient gain, but will decrease both the amplitude of the transient absorption and the steady-state value. We also found that the transient behavior relies on other parameters, such as the radiative decay rate and pure dephasing decay rate of QDs.

Acknowledgments

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