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Phase control of optical bistability based biexciton coherence in a quantum dot nanostructure

Seyyed Hossein Asadpour [1], H. Rahimpour Soleimani*

Department of Physics, University of Guilan, Rasht, Iran

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ABSTRACT

In this paper, phase control of optical bistability and multistability based biexciton coherence is investigated in GaAs/$Al_xGa_{1-x}As$ semiconductor structure with 15 periods of 17.5 nm GaAs layer and 25-nm $Al_{0.3}Ga_{0.7}$ barriers, grown by molecular beam epitaxy, four-level quantum dot nanostructure. By two control fields that couple to a biexciton state, the destructive interference can be obtained. In this case, the optical bistability (OB) and optical multistability (OM) can be dramatically altered with adjusting the absorption of two weak probe and signal fields. The results show that the OB and OM behavior of the medium are different for two-weak-pulsed probe fields due to effect of exciton spin relaxation, intensity of coupling fields and relative phase between applied fields.

1. Introduction

It is well known that quantum interference and atomic coherence lead to the many interesting phenomena in quantum and nonlinear optics. Electromagnetically induced transparency (EIT) [1,2], lasing without inversion (LWI) [3], four wave mixing (FWM) [4–6], coherent population trapping (CPT) [7] and another interesting phenomena have been widely studied experimentally and theoretically in various atomic systems by many research groups [8–20]. It is known that by considering the quantum interference via two-photon resonance transitions, the opaque three-level medium becomes transparent one due to cancelation of transition between dark and excited states, thus in this case the EIT is generated [21]. The most popular three-level systems in quantum optics are Λ, Ξ and V system [22–24], which have different effects under the action of different driving fields. The effect of EIT has many applications in quantum optics and especially in quantum information science and technology. More complicated level structure such as tripod four-level [25], the N-type system [26] and inverted Y-type atomic model [27] have been discussed more physically in recent years. It is shown that the EIT leads to the photon information storage and release in an atomic system [28], correlated photon pairs generation [29], entanglement of remote atomic assembles [30] and optical bistability [31]. Moreover, optical bistability (OB) due to its wide applications in all-optical switching and all-optical storage in various media have been extensively studied theoretically and experimentally [32–41]. For example, e theoretical model of OB in a two-level atom with single mode field was discussed by Rosenberger [35], Joshi et al. displayed theoretically and experimentally the realization of OB in a three-level atomic system embedded in an optical ring cavity [36,37]. Moreover, the transition from OB to optical multistability (OM) or vice versa by adjusting the relative phase between applied fields was investigated in a double two-level atomic medium [42]. Recently, experimental observation of OM in an optical ring cavity confined by three-level rubidium atoms is studied by Sheng et al. [43]. Furthermore, the effect of squeezed state field [44], spontaneously generated coherence [45], the phase fluctuations [46,47], the intensity of microwave field [48], on OB and OM has been shown theoretically. In our recent study, we showed that OB and OM can be occurred in a parametric region [49]. In another study, the effect of open atomic system in OB and OM is also discussed [50]. It was shown that by, by adjusting the ratio between atomic injections and exit rates from the cavity, the intensity threshold of optical bistability can be controlled.

On the other hand, it should be pointed out that similar phenomena involving quantum coherence and quantum interference in solid state systems have also attracted great attention due to the potentially important applications in optoelectronics and solid state information sciences [51,52]. It has been shown that they can lead to EIT [53], gain without inversion [54], coherently controlled photocurrent generation [55]. It is worth pointing out that Zhao et al. [56] reported microwave-induced absorption changes in ruby, while Ham et al. [57] described transmittance changes induced by visible light in $Pr^{+3}:Y_2SiO_5$. The observation

* Corresponding author.
E-mail addresses: s.hosein.asadpour@gmail.com (S. Hossein Asadpour), rahimpour@guilan.ac.ir (H. Rahimpour Soleimani).
[1] Tel./fax: +98 1313220066.

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of coherent phenomena such as EIT and LWI in semiconductor materials are difficult due their large ($\sim 100\,\mathrm{fs}^{-1}$) dephasing rates. However, devices based on intersubband transitions in semiconductor quantum well structure have many inherent advantages, such as large electric dipole moments due to the small effective electron mass, high nonlinear optical coefficients, and a great flexibility in device design by choosing the materials and structure dimensions. Furthermore, the transition energies, dipoles, and symmetries can be engineered. Note that the implementation of EIT in semiconductor-based devices is very attractive from view point of applications. The theory of quantum coherence phenomena in semiconductor quantum dot (QD) was also introduced by Chow [58].

One of the most distinguished features in the coherent optical response of a semiconductor arising from Coulomb-correlation effects is the spectral signature of the bound-biexciton state. Under ultrashort-pulse excitation the coherent dynamics of the optically generated electron–hole pairs is strongly governed by correlation effects induced by the Coulomb interaction among them [59]. With intersubband coherence between different conduction subbands [60–62] and different valance subbands [63], and with intervalence band coherence between the heavy-hole (HH) and light-hole (LH) valance bands [64,65], EIT processes have also been observed. EIT may lead to great enhancement in nonlinear effects and steep dispersion, as well as to the reduction of group velocity, the storage of optical pulses [66,67] and controlling the intensity threshold of optical bistability [68–73]. In these proposals, it has been shown that the OB threshold intensity can be significantly controlled by effect of quantum coherence and interference in semiconductor nanostructure. For example, Li et al. studied the behavior of OB in a triple semiconductor quantum well structure with tunneling induced interference [72], Wang and Yu, reported OB behavior in an asymmetric three-coupled quantum well inside a unidirectional ring cavity via coherent driven field [73].

In this paper, the optical bistability and multistability in a four-level biexciton–exciton cascade configuration inside a unidirectional ring cavity is investigated. Coulomb correlations between excitons with opposite spins can lead to the formation of biexciton. The quantum interference is set up by two control pulses that couples to a resonance of the biexciton. It shows that OB and OM behaviors of two weak fields can be controlled by … and adjusting the relative phase between applied control fields.

2. Model and equations

We consider here GaAs/Al$_x$Ga$_{1-x}$As semiconductor structure with 15 periods of 17.5 nm GaAs layer and 25-nm Al$_{0.3}$Ga$_{0.7}$ barriers, grown by molecular beam epitaxy. The energy level structure is given by the ground state as $|0\rangle$, the linearly polarized (i.e., the symmetric and antisymmetric combination of spin-up and down) exciton states as $|1\rangle$ and $|2\rangle$, and the biexciton state of the two antiparallel-spin excitons due to Coulomb coupling as $|3\rangle$ [74]. The four-level quantum dot interacts with two CW laser control fields that couple transitions $|1\rangle \leftrightarrow |3\rangle$ and $|2\rangle \leftrightarrow |3\rangle$ with angular frequencies ω_{c1}, ω_{c2} and Rabi frequencies $2\Omega_{c1,\,c2}$ respectively. The two pulsed probe and signal fields drive the transitions $|0\rangle \leftrightarrow |1\rangle$ and $|0\rangle \leftrightarrow |2\rangle$ with angular frequencies ω_p, ω_s and Rabi frequencies $2\Omega_{p,\,s}$. Here, two exciton states corresponds to ($|1\rangle$ and $|2\rangle$), and biexciton state corresponds to $|3\rangle$ (Fig. 1). The value of the biexciton binding energy ΔE is several meV [75]. Also, we assume each laser pulse to drive only one transition. The time evolution of the system, expressed using the density operator ρ, is governed by the Liouville equation which, under the electric-dipole and rotating-wave approximation, leads to the following equations for the density matrix elements ρ_{ij}

$$\begin{aligned}
\dot{\rho}_{11} &= i\Omega_p(\rho_{01}-\rho_{10})+i\Omega_{c1}(\rho_{31}-\rho_{13})+\gamma_a\rho_{22}-(\gamma_b+\gamma_4)\rho_{11}+\gamma_2\rho_{33}\\
\dot{\rho}_{22} &= i\Omega_s(\rho_{02}-\rho_{20})+i\Omega_{c2}(e^{i\phi}\rho_{32}-e^{-i\phi}\rho_{23})+\gamma_1\rho_{33}\\
&\quad -(\gamma_3+\gamma_a)\rho_{22}+\gamma_b\rho_{11}\\
\dot{\rho}_{33} &= +i\Omega_{c2}(e^{-i\phi}\rho_{23}-e^{i\phi}\rho_{32})+i\Omega_{c1}(\rho_{13}-\rho_{31})-(\gamma_1+\gamma_2)\rho_{33}\\
\dot{\rho}_{10} &= -(1/2(\gamma_4+\gamma_b+\gamma_{10}^{dph})-i\Delta_1)\rho_{10}+i\Omega_p(\rho_{00}-\rho_{11})\\
&\quad +i\Omega_{c1}\rho_{30}-i\Omega_s\rho_{12}\\
\dot{\rho}_{20} &= -(1/2(\gamma_3+\gamma_a+\gamma_{20}^{dph})-i\Delta_2)\rho_{20}+i\Omega_s(\rho_{00}-\rho_{22})\\
&\quad +i\Omega_{c2}e^{i\phi}\rho_{30}-i\Omega_p\rho_{21}\\
\dot{\rho}_{30} &= -(1/2(\gamma_1+\gamma_2+\gamma_{30}^{dph})-i\Delta_3)\rho_{30}+i\Omega_{c1}\rho_{10}+i\Omega_{c2}e^{-i\phi}\rho_{20}\\
&\quad -i\Omega_s\rho_{32}-i\Omega_p\rho_{31}\\
\dot{\rho}_{32} &= -(1/2(\gamma_1+\gamma_2+\gamma_3+\gamma_{32}^{dph})-i(\Delta_3-\Delta_1))\rho_{32}-i\Omega_{c2}e^{i\phi}(\rho_{33}-\rho_{22})\\
&\quad -i\Omega_{c1}\rho_{21}+i\Omega_s\rho_{03}\\
\dot{\rho}_{21} &= -(1/2(\gamma_b+\gamma_3+\gamma_4+\gamma_a+\gamma_{21}^{dph})-i(\Delta_1-\Delta_2))\rho_{21}-i\Omega_p\rho_{20}\\
&\quad -i\Omega_{c1}\rho_{23}+i\Omega_{c2}e^{i\phi}\rho_{31}+i\Omega_s\rho_{01}\\
\dot{\rho}_{31} &= -(1/2(\gamma_1+\gamma_2+\gamma_4+\gamma_b+\gamma_{31}^{dph})-i(\Delta_1-\Delta_3))\rho_{31}+i\Omega_p\rho_{03}\\
&\quad +i\Omega_{c1}(\rho_{33}-\rho_{11})-i\Omega_{c2}e^{i\phi}\rho_{12}
\end{aligned} \tag{1}$$

where

$$\rho_{ij}=\rho_{ij}^{*},\ \Delta_j=\omega_{p(s)}-(\omega_j-\omega_0)\ (J=1,2),\ \Delta_3=\omega_{p(s)}+\omega_{cj}-(\omega_3-\omega_0)$$

The latter, γ_{ij}^{dph} is the dephasing broadening linewidth, which may originate from electron–electron scattering, electron–phonon scattering as well as inhomogeneous broadening due to scattering on interface roughness. Generally, γ_{ij}^{dph} is the dominant mechanism in a semiconductor solid state system in contrast to the atomic system. Now, we consider a medium of length L composed of the above described QW structure immersed in unidirectional ring cavity based on Refs. [68–73]. Under slowly varying envelop approximation; the dynamic response of the probe and signal field are governed by Maxwell's equations,

$$\frac{\partial E_p}{\partial t}+c\frac{\partial E_p}{\partial z}=\frac{i\omega_p}{2\varepsilon_0}P(\omega_p). \tag{2a}$$

$$\frac{\partial E_s}{\partial t}+c\frac{\partial E_s}{\partial z}=\frac{i\omega_p}{2\varepsilon_0}P(\omega_s). \tag{2b}$$

$P(\omega_{p(s)})$ is induced polarization in the transitions $|0\rangle \to |1\rangle$ and $|0\rangle \to |2\rangle$ it is given by

$$P(\omega_{p(s)})=N\mu(\rho_{10(20)}), \tag{3}$$

Substituting Eq. (3) into Eqs. (2a) and (2b), one can obtain the field amplitude relation for the steady state as follow:

$$\frac{\partial E_{p(s)}}{\partial z}=i\frac{N\omega_{p(s)}\mu}{2c\varepsilon_0}(\rho_{10(20)}), \tag{4}$$

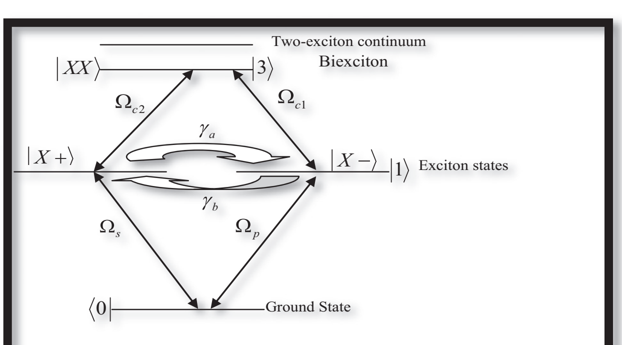

Fig. 1. Model for a single QD. $|0\rangle$ Ground state, $|1\rangle$ and $|2\rangle$ one biexciton state, $|3\rangle$ biexciton state (or two-exciton continuum state). The QD interacts with two laser control fields and two pulsed probe fields.