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Optical bistability and multistability via biexciton coherence in semiconductor quantum well nanostructure

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ABSTRACT

In this paper, we report theoretical investigation of controlling the optical bistability (OB) and optical multistability (OM) in a GaAs quantum well inside a unidirectional ring cavity. In this scheme quantum interference is raised by a control pulse that couples to a resonance of a biexcitons. It is shown that many-particle interactions which are natural in semiconductors can be used to creation of quantum coherence. In this case optical bistability and multistability can be controlled by biexciton energy renormalization which resulted from many-particle coulomb interactions.

1. Introduction

It is known that controlling light by light is an essential for the next generation of all optical and quantum networks. Therefore, for the manipulation and controlling of optical response to the weak and strong electromagnetic field quantum coherence and interference should be studied in the various media. Coherent utilization of quantum coherence and interference in atomic systems has led to an unforeseen phenomena such as electromagnetically induced transparency (EIT) [1], lasing without inversion (LWI) [2], four wave mixing [3–5], slow and stopped light [6,7], giant Kerr nonlinearity [8–10], superluminal light propagation [11], optical bistability (OB) [12–15] and so on [16–20].

Recently for development and application of all optical systems in photonic devices such as all optical switches, optical modulators and variable true time delays [21–23], researchers are very interested to supersede atomic systems to semiconductor quantum wells (QWs) and quantum dot (QDs) nanostructure. Quantum wells and quantum dots have discrete energy levels and their optical properties are very similar to atomic systems [24,25]. They have also inherent beneficial such as high nonlinear optical coefficients and large electric dipole moments. There have been a large number of efforts on investigate the electromagnetically induced transparency in semiconductors quantum wells medium experimentally and theoretically due to it wide applications in all optical and quantum networks [26]. For example, observation of EIT via biexciton coherence reported by Ma et al. in GaAs/AlGaAs multiple quantum wells (MQWs) [27]. Studies on semiconductor QWs can also successfully simplify the realization the nature of quantum coherences in semiconductors and the eventual performance of optical devices based on the coherence phenomena.

Excitons play an essential role in optical processes near the fundamental band edge in direct-gap semiconductors. EIT processes based on excitonic nonraditive coherence, including exciton spin coherence and biexciton coherence, have been demonstrated in quantum wells [28–30]. By predominant the rapid decoherence with ultrafast laser pulses and by using and restrains the many-body Coulomb interactions, the realization of the excitonic EIT processes in QWs has been made possible. With intersubband coherence between different conduction subbands [31–33] and different valance subbands [34], and with intervalence band coherence between the heavy-hole (HH) and light-hole (LH) valance bands [35,36], EIT processes have also been observed. Various EIT processes have also been explored experimentally [37] as well as theoretically in QDs [38–40]. 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 [41,42] and controlling the intensity threshold of optical bistability [43–45]. Optical bistability has been developed due to its potential application in all optical switching and optical transistors which are necessary for quantum computing and quantum communications. Optical bistability and multistability processes in hot and cold atomic media have been proposed theoretically and experimentally in recent years [46–48]. In these proposals, it has been shown that the OB and OM threshold intensity can be significantly controlled by effect of quantum coherence and interference.

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The similar phenomena involving OB and OM in semiconductor quantum wells system have also attracted great attention due to the potentially important applications in optoelectronics and solid-state quantum information science [49–52]. For example, Li et al. studied the behavior of OB in a triple semiconductor quantum well structure with tunneling induced interference [53], Wang and Yu, reported OB behavior in an asymmetric three-coupled quantum well inside a unidirectional ring cavity via coherent driven field [54].

In this paper, we study the optical bistability in a GaAs quantum well inside a unidirectional ring cavity. Coulomb correlations between excitons with opposite spins can lead to the formation of biexciton. The quantum interference is set up by a control pulse that couples to a resonance of the biexciton. It is shown that by controlling the coupling pulse, many-particle Coulomb interaction such as biexciton energy renormalization and detuning of the probe pulse, one can control the threshold of the optical bistability and multistability.

2. Model and equations

To realize the optical bistability and multistability in semiconductor MQWs, we use of biexciton coherence. In GaAs MQWs, the energy level structure can be realized in a three-level system [see Fig. 1(a)] where a control beam drives the transition $|2\rangle \rightarrow |3\rangle$ and set up a destructive interference for a weak probe beam coupling to the transition $|1\rangle \rightarrow |2\rangle$. In other words, a control beams drives 1s-exciton states to biexciton transition and weak probe beam couples ground state $|g\rangle$ to 1s-exciton state transition. Our effective three-level configuration is obtained by focusing on interband transitions in a GaAs MQWs between the conduction bands with spin $S_z = \pm 1/2$ and the heavy-hole (HH) valance bands with $m_j = \pm 3/2$. By using of circularly polarized light, $\sigma+$ and σ-excitons is excited via $\sigma+$ and σ-transitions, respectively. While these two transitions share no common state, correlations between excitons with opposite spins which caused by coulomb interaction, can lead to the formation of bound two-exciton (biexciton) states [Fig. 1(c)]. Biexciton coherence arises from coherent superposition between the ground and biexciton states induce destructive interference in the GaAs MQWs [55,56]. Under the rotating wave approximation, the set of density matrix equation can be obtained for the three-level system as follows [57]:

$$\dot{\rho}_{xg} = [i\Delta_p - \gamma]\rho_{xg} + i\Omega_c\rho_{bg}/2 + i\Omega_p/2,$$
$$\dot{\rho}_{bg} = [i(\Delta_p - \Delta_c) - \gamma_b]\rho_{bg} + i\Omega_c\rho_{xg}/2 \quad (1)$$

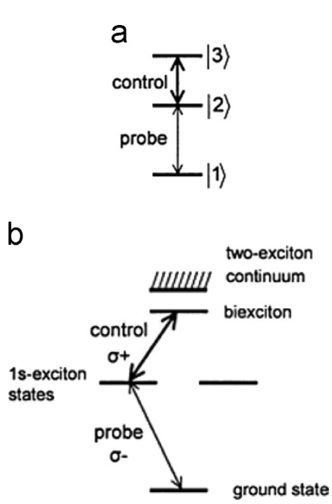

Fig. 1. A three-level cascade system. © Schematic of energy eigenstates for the ground, one-exciton, and two-exciton states [30].

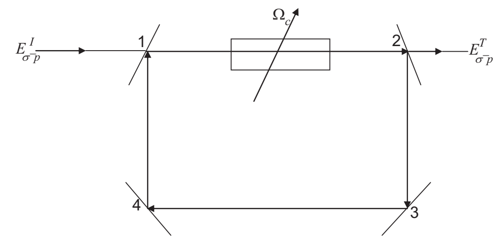

Fig. 2. Unidirectional ring cavity with GaAs quantum well sample of length L.

where ρ_{xg} and ρ_{bg} are the exciton and biexciton coherence, respectively. $\Delta_p = \omega_p - \omega_x$, $\Delta_c = \omega_c - \omega_b$, are detuning parameters of the Rabi frequency Ω_p and Ω_c. ω_x (ω_b) and γ (γ_b) are the resonance frequency and decay rate for the exciton (biexciton) coherence, and ω_c (ω_p) are the optical frequency for the control (probe). The value of the biexciton binding energy is based to Ref. [58].

Now, we consider a medium of length L composed of the above described QW structure immersed in unidirectional ring cavity as shown in Fig. 2. The intensity reflection and transmission coefficients of mirrors 1 and 2 are R and T (with $R+T=1$), respectively. It is assumed that both the mirrors 3 and 4 are prefect reflectors. The total electromagnetic field can be written as:

$$E = E_{\sigma-p}e^{i\omega_p t} + E_{\sigma+}e^{i\omega_c t} + C \times C \quad (2)$$

where $E_{\sigma-p}$ is the amplitude of the probe field circulating in the ring cavity, $E_{\sigma+}$ is the amplitude of the coupling fields where is not circulate in the cavity. Under slowly varying envelop approximation; the dynamic response of the probe field is governed by Maxwell's equations,

$$\frac{\partial E_{\sigma-p}}{\partial t} + c\frac{\partial E_{\sigma-p}}{\partial z} = \frac{i\omega_p}{2\varepsilon_0}P(\omega_p), P(\omega_p) \quad (3)$$

is induced polarization in the transitions $|g\rangle \rightarrow |x\rangle$ and it is given by

$$P(\omega_p) = N\mu(\rho_{xg}), \quad (4)$$

Substituting Eq. (4) into Eq. (3), one can obtain the field amplitude relation for the steady state as follows:

$$\frac{\partial E_{\sigma-p}}{\partial z} = i\frac{N\omega_p\mu}{2c\varepsilon_0}(\rho_{xg}), \quad (5)$$

The coherent field $E^I_{\sigma-p}$ from mirror M_1, interacts with the atomic sample of length L, circulates in the cavity, and partially comes out of the mirror M_2 as $E^T_{\sigma-p}$. The probe field at the start of the atomic sample is $E_P(0)$ and at the end of the atomic sample it increases up to $E_{\sigma-P}(L)$ in a single pass transition. The coupling field can also enter the cavity through the polarizing beam splitter and co-propagates with the cavity field in the atomic cell. For a perfectly tuned cavity, the boundary conditions in the steady-state limit between the incident field $E^I_{\sigma-p}$ and transmitted field $E^T_{\sigma-p}$ are [59,60]:

$$E_{\sigma-p}(L) = \frac{E^T_{\sigma-p}}{\sqrt{T}}, \quad (6)$$

$$E_{\sigma-p}(0) = \sqrt{T}E^I_{\sigma-p} + RE_{\sigma-p}(L), \quad (7)$$

where L the length of the atomic sample, R is the feedback mechanism due to the reflection from mirror M_2 and it is responsible for the bistable behavior. Therefore; one does not expect any bistability for $R=0$ in Eq. (7). According to the mean-field limit [61] and by using of the boundary conditions the steady state behavior of $\sigma-$polarized transmitted field is given by:

$$y = 2x - i\,C\,(\rho_{xg}) \quad (8)$$