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Transmission and reflection properties of propagated pulse through defect slab based biexciton coherence

Seyyed Hossein Asadpour*, H. Rahimpour Soleimani

Department of Physics, University of Guilan, Rasht, Iran

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ABSTRACT

In this paper, we theoretically investigate transmission and reflection properties of incident light through dielectric medium doped by GaAs/AlGaAs multiple quantum wells with 15 periods of 17.5 nm GaAs wells and 15-nm $Al_{0.3}$ $Ga_{0.7}As$ barriers, grown by metal organic chemical vapor deposition. The destructive quantum interference is set up by a control pulse that couples to a resonance of biexcitons. We found that many-particle interactions such as biexciton binding energy and biexciton decoherence which are inherent in semiconductors can affect the transmission and reflection properties of incident light on the slab. We have also shown that simultaneous subluminal or superluminal transmission, reflection can be achievable at different frequencies of probe field.

1. Introduction

Propagation of an incident pulse through a dispersive medium has been extensively discussed by many research groups [1]. Coherent control of optical properties of a dispersive medium leads to observation of many interesting phenomena such as electromagnetically induced transparency (EIT) [2], lasing without population inversion (LWI) [3], four wave mixing (FWM) [4–6], dark and bright optical solitons [7], optical bistability [8–11], superluminal light propagation [12] and so on [13–18]. Similar phenomena based on the quantum interference and coherence in semiconductor quantum wells (SQWs) and quantum dots (SQDs) have also been extensively studied recently [19–41], for example lasing without inversion [19–21], electromagnetically induced transparency [22–25], optical bistability and multistability [26–31], Kerr nonlinearity [32–34], four-wave mixing [35–38], electron localization [39], probe absorption [40] and transient electron population [41]. In Ref. [41], Wang et al. discussed transient behaviors of the dispersion and absorption in three-level SQWs. They found that the Fano interference and the energy splitting affect the transient behaviors dramatically, which can be used to manipulate efficiently the gain-absorption coefficient and group velocity of the probe field. The transient electron population on the Fano interference and energy splitting was also discussed. 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 structural dimensions. Furthermore, the transition energies, dipoles, and symmetries can be engineered [42,43].

In a single atomic system, both theoretical and experimental studies have been done to investigate subluminal and superluminal light propagation via quantum coherence and interference [44]. The effect of intensity of coupling fields [45] and relative phase between applied fields [46] on subluminal and superluminal light propagation has been investigated. The effect of incoherent pumping field and quantum interference on the group velocity of incident pulse has also been discussed [47,48]. Kim et al. reported experiments in which with electromagnetically induced absorption (EIA), the superluminal and subluminal light propagation can be obtained in Cs vapor [49]. All of the above proposals on subluminal and superluminal light propagation are observed in atomic systems. However, light propagation in a solid state material such as slab or photonic crystal (PCs) has been discussed by many research groups [50]. One of the slab advantage of slab systems over gas systems is that in gas systems only subluminal or superluminal light propagation can be provided, while in the slab system, the superluminal pulse reflection and the superluminal pulse transmission can be achieved simultaneously [50]. In Ref. [50], the possibility of light reflection and transmission in a slab system doped with two-or three-level atomic systems without introducing the explicit dependence of the group velocity on controlling parameters is discussed. Jafari et.al. investigated propagation of an electromagnetic pulse through a dielectric slab doped with a three-level ladder-type atomic system. They found

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* Corresponding author. Tel./fax: +98 1313220066.
E-mail address: s.hosein.asadpour@gmail.com (S.H. Asadpour).

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that the group velocity of the reflected and transmitted pulses can be switched from subluminal to superluminal light propagation by the thickness of the slab, intensity of the coupling field and quantum interference from spontaneous emission [51]. However, according to our knowledge, the important proposal on light transmission and light reflection from slab system is discussed in Ref. [50]. In this study, the possibility of light reflection and transmission in a slab system doped with two or three-level atoms without introducing the explicit dependence of the group velocity on controlling parameters such as intensity and relative phase of applied field is presented. Moreover, in our recent study, we showed that transmission and reflection properties of incident pulse in a slab doped by quantum dot nanostructure can be controlled. We showed that electron tunneling between electron states of quantum dot can affect transmission and reflection properties of propagated light at different wavelengths [52]. In another work, we displayed the effect of electron spin coherence on superluminal and subluminal pulse propagation in a dielectric slab doped by quantum well waveguide [53]. We found that spin coherence has an essential role to play in switching from subluminal to superluminal light propagation in a dielectric slab. However, in the above works, the majority of the theoretical analyses of quantum-coherence effects in quantum wells and quantum dots are based on atomic quantum coherence theory [54]. They do not contain a complete description of many-body effect such as Coulomb interaction between charged carriers. In this paper, we investigate theoretical studies on transmitted and reflected pulses from defect slab doped by GaAs multiple quantum wells based exciton spin coherence (ESC) and biexciton coherence. Here, the spin coherence arises from correlation between excitons with opposite spins due to Coulomb correlations. The Coulomb correlation between excitons states (spin-up and spin-down), which can be excited with σ^+ and σ^- circularly polarized light, can lead to the formation of biexciton states [55–62]. Therefore, ESC can be induced via the exciton to biexciton transition with opposite spins. In our recent studies, we studied the effect of spin coherence and biexciton coherence on optical bistability and multistability [63,64]. In Ref. [63], we showed that spin coherence can affect the optical bistability and multistability. In Ref. [64], the effects of biexciton coherence and biexciton energy renormalization on optical bistability and multistability were discussed. In this paper, we propose a theoretical scheme for controlling the superluminal and subluminal light transmission and reflection in a slab doped by multiple quantum wells nanostructure. We show that many-particle interactions which are inherent in semiconductors and are often detrimental to quantum coherence can affect the transmission and reflection properties of incident pulse in a defect slab system. We hope that our proposed model may be helpful for the future experimental works based many-particle interaction in the semiconductors. Note that, although the light propagation discussed here resembles that of an atomic system, the biexciton coherence itself is a direct result of many-particle Coulomb correlations and can thus lead to behaviors qualitatively different from those on an atomic system. First and foremost is that we are interested in showing the controllability of the simultaneous subluminal and superluminal light propagation in a defect slab dope by GaAs/AlGaAs multiple quantum wells via biexciton coherence. Second, the superluminal and subluminal light transmission and reflection can easily be controlled by adjusting the biexciton energy renormalization and biexciton decoherence which are not in usual three-level atomic systems. Third, very important advantages of our investigation can be used for the optimal design of semiconductor QW systems to achieve transmitted and reflected devices, which is much more practical than that in an atomic system because of its flexible design and controllable interference strength.

2. Model and equation

2.1. Pulse propagation

Consider a weakly absorbing and nonmagnetic slab with the complex relative permittivity $\varepsilon(\omega_p)=\varepsilon_r+i\varepsilon_i$ where ε_r and ε_i correspond to the dispersion and absorption part respectively [50,51]. For a TE plane wave, the transfer matrix for the electric and magnetic components of a monochromatic wave of frequency ω through the slab is given by [50]:

$$\begin{pmatrix} \cos(kd) & i\frac{1}{n(\omega_p)}\sin(kd) \\ in(\omega_p)\sin(kd) & \cos(kd) \end{pmatrix}, \tag{1}$$

where $n(\omega_p)=\sqrt{\varepsilon_p}$ represent the refractive index of the slab. It is assumed that the slab is doped with GsAs multiple quantum wells (MQWs) with 17.5 nm GaAs wells and 15 nm $Al_{0.3}Ga_{0.7}$ barriers. We assume that the dielectric function can be separated into two parts

$$\varepsilon(\omega_p)=\varepsilon_b+\chi(\omega_p), \tag{2}$$

where ε_b is the surroundings dielectric functions and $\chi(\omega_p)$ is the susceptibility of quantum well doped in the slab. Using the transfer-matrix method, the reflection and transmission coefficients of the monochromatic wave can be obtained as [50]

$$r(\omega_p)=\frac{-(i/2)(1/\sqrt{\varepsilon}-\sqrt{\varepsilon})\sin(kd)}{\cos(kd)-(i/2)(1/\sqrt{\varepsilon}+\sqrt{\varepsilon})\sin(kd)}, \tag{3}$$

$$t(\omega_p)=\frac{1}{\cos(kd)-(i/2)(1/\sqrt{\varepsilon}+\sqrt{\varepsilon})\sin(kd)}, \tag{4}$$

where it is assumed that $\varepsilon_b=4$.

From Eqs. (3) and (4), it is found that the reflection and transmission coefficients depend on the thickness and the refractive index of the slab. For the resonance condition, the thickness of the slab is employed as $d=2m(\lambda_0/4\sqrt{\varepsilon_b})$, whereas, for the off-resonance condition, it is considered as $d=(2m+1)(\lambda_0/4\sqrt{\varepsilon_b})$. Here, m is an integer number, and in the following numerical calculations is chosen as $m=100$. A subluminal pulse reflection or transmission corresponds to peak in the curve of the reflectivity and transmittivity, while a dip corresponds to superluminal pulse reflection or transmission.

2.2. GaAs/AlGaAs multiple quantum wells nanostructure

In GaAs/AlGaAs multiple quantum wells with 15 periods of 17.5 nm GaAs wells and 15-nm $Al_{0.3}$ $Ga_{0.7}As$ barriers, grown by metal organic chemical vapor deposition, 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 beam drives 1s-exciton states to biexciton transition and weak probe beam couples ground state $|1\rangle$ to 1s-exciton state transition. Correlations between excitons with opposite spins which are caused by Coulomb interactions can lead to the formation of bound two-exciton (biexciton) states. In the absence of Coulomb interactions, these two exciton states can be factored into product states of single excitons, the system is reduced and no biexciton coherence can be induced. Our effective three-level configuration is obtained by focusing on interband transitions in GaAs MQWs between the conduction bands with spin $S_z=\pm 1/2$ and the heavy-hole (HH) valence bands with $m_j=\pm 3/2$. By using circularly polarized light, $\sigma+$ and $\sigma-$ excitons are excited via $\sigma+$ and $\sigma-$ transitions, respectively [Fig. 1(b)]. Biexciton coherence arises from coherent superposition between the ground and biexciton states inducing destructive interference in the GaAs MQWs [65,66]. We apply a σ^+ pump to