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Theoretical ultraslow bright and dark optical solitons in cascade-type GaAs/AlGaAs multiple quantum wells

Wei Yan, Tao Wang *, Xiao-Ming Li

Wuhan National Laboratory for Optoelectronics, College of Optoelectronic Science, Engineering, Huazhong University of Science, Technology, Wuhan 430074 , Hubei, PR China

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ABSTRACT

We show the formation of ultraslow bright and dark optical solitons in a cascade-type three-level system of GaAs/AlGaAs multiple quantum wells (MQWs) structure based on the biexciton coherence in the transient optical response, and study analytically and numerically with Maxwell–Schrödinger equations. The calculated velocity of bright and dark optical solitons are $V_g = 2.7 \times 10^4\ ms^{-1}$ and $V_g = 8.91 \times 10^4\ ms^{-1}$, respectively. Such investigation of ultraslow optical solitons in MQWs may provide practical applications such as high-fidelity optical delay lines and optical buffers in semiconductor quantum wells structure, because of its flexible design.

1. Introduction

Over the past few years, a great deal of nonlinear quantum optical phenomena based on atomic coherence and quantum interference has been studied in atomic regime by many groups. The subject of extensive theoretical and experimental investigations on optical solitons, describing a class of fascinating shaping-preserving wave propagation phenomena in nonlinear media, has received much attention mainly due to its potential wide applications in optics communication, wave propagation, and quantum information science [1–6]. In fact, the study of ultraslow optical solitons is motivated by using a conventional electromagnetically induced transparency (EIT) technique to enhance Kerr nonlinearities. In particular, this technique has been proposed for achieving a large nonlinear phase shift with weak control optical fields. Furthermore, the technique has been shown to be beneficial to certain nonlinear optical processes under weak driving conditions where the ultraslow propagation is a dominant feature. These enhancement effects under ultraslow propagation conditions naturally lead to the formation of optical solitons in a highly resonant nonlinear medium [3–9]. Recently, optical solitons including two-color solitons with very low group velocities, based on Raman excitation, have been systematically proposed by Wu and Deng [3,4]. Consequently, the dynamics of ultraslow optical solitons in cold atomic medium were studied [7–10]. The similar phenomena involving EIT, ultraslow propagation of optical pulses, and four-wave mixing in semiconductor quantum wells systems have also attracted great attention due to the potentially important applications in optoelectronics and solid-state quantum information science [2,6,11–16]. For example, Ku et al. reported slow light via PO, which use a process of coherent wave mixing with continuous wave (CW) laser in GaAs/AlGaAs MQWs [2]. Hao et al. reported the formation of an efficient four-wave mixing in an asymmetric semiconductor double quantum-well structure based on intersubband transitions [6]. Phillips et al. reported experimental studies of EIT arising from exciton spin coherence in the transient optical response in a Λ-type three-levee system of GaAs quantum wells [14]. However, the ultraslow solitons in cascade-type three-level system of GaAs/AlGaAs MQWs have less been reported.

In this paper, we shall report the formation of ultraslow bright and dark optical solitons in a cascade-type three-level system of GaAs/AlGaAs multiple quantum wells (MQWs) structure based on the biexciton coherence in the transient optical response, and study analytically and numerically with Maxwell–Schrödinger equations. The calculated velocity of bright and dark optical solitons is $V_g = 2.7 \times 10^4\ ms^{-1}$ and $V_g = 8.91 \times 10^4\ ms^{-1}$, respectively.

2. Theoretical calculation

Our study to realize the optical solitons in semiconductor MQWs have exploited the use of biexciton coherence. For semiconductors such as a GaAs MQW, the energy level structure can be realized in a three-level system where a control beam drives 1s-exciton states to biexciton (or two-exciton continuum) transition and sets up a destructive interference for a weak probe beam coupling to the $|g\rangle \rightarrow$ 1s-exciton state transition [see Fig. 1]. For our effective three-level scheme, we focus on interband transitions in a GaAs MQWs between the conduction bands with spin $S_z = \pm 1/2$ and the heavy-hole (HH)

* Corresponding author.
E-mail address: wangtao@hust.edu.cn (T. Wang).

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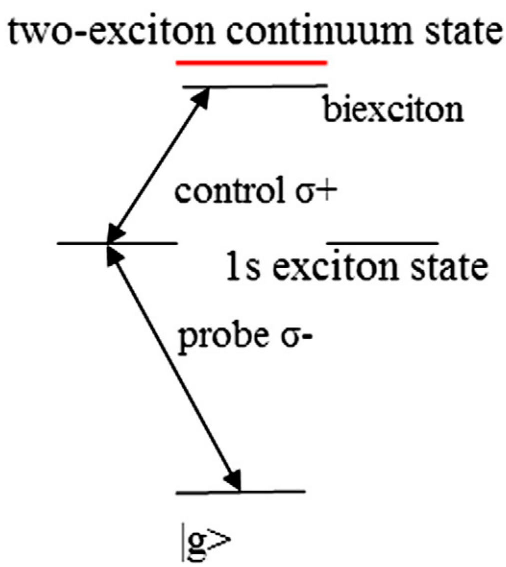

Fig. 1. Schematic energy-level diagram for a GaAs multiple quantum wells. |g> ground state, single exciton state, biexciton (or two-exciton continuum state).

valence bands with $J_s = \pm 3/2$. Using circularly polarized light, we can excite σ+ and σ− excitons via σ+ and σ− transitions, respectively. While these two transitions share no common state, correlation (caused by the Coulomb interaction) between excitons with opposite spins can lead to the formation of bund two-exciton (biexciton) states or unbound two-exciton continuum.

For simplification, we denote the ground state |g>, 1s-exciton state and biexciton state by |1>, |2> and |3>, respectively [see Fig. 2], and allow each laser pulse to drive only on transition. In the interaction picture, with rotating-wave approximation and the electric-dipole approximation, the free and interaction Hamiltonian of the system under study can be respectively written as (taking = 1)

$$H_0 = \omega_p|2><2| + \left(\omega_p + \omega_c\right)|3><3| \tag{1}$$

$$H_{\rm int} = \Delta_p|2><2| + \left(\Delta_p + \Delta_c\right)|3><3| - \left(\Omega_p|2><1| + \Omega_c|3><2| + \text{H.c}\right) \tag{2}$$

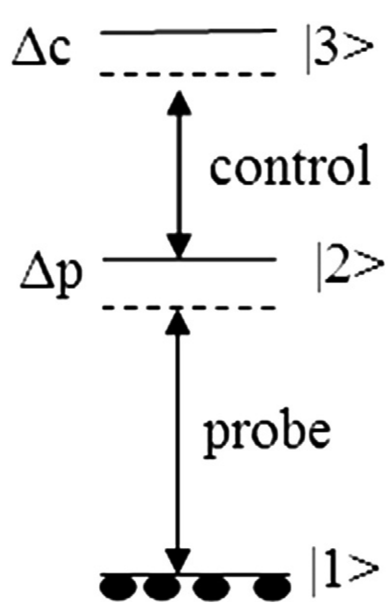

Fig. 2. A simplified cascade three-level scheme in GaAs multiple quantum wells.

where $\Delta_p = [(\epsilon_2 - \epsilon_1)/\hbar] - \omega_p$ and $\Delta_c = [(\epsilon_3 - \epsilon_2)/\,] - \omega_c$ are the detuning of probe pulse and pump (control) pulse, with ϵ_1, ϵ_2, ϵ_3 and ω_p, ω_c being the energy of state |1>, |2>, |3> and the frequency of the probe pulse,pump pulse, respectively. Also, $\Omega_p = D_{21}E_P/2\hbar$ and $\Omega_c = D_{32}E_c/2\hbar$ are the Rabi frequencies of the probe pulse and pump pulse, respectively, with D_{21},, D_{32} being the corresponding dipole transition matrix element. H.c means Hermitian conjugation. In the above derivation process, we have taken the ground state |1> as the energy origin for simplicity. As we all know, the electronic energy state can be written as

$$\Psi = A_1|1> + A_2|2> + A_3|3>$$

where A_j $(j = 1-3)$ stands for the time-dependent probability amplitude of finding the electron in level |j>. Making use of the Schrödinger equation $i\partial\Psi/\partial t = H_{\rm int}\Psi$, the equations of motion for the probability amplitude for the electronic wave functions can be readily obtained as

$$\frac{\partial A_1}{\partial t} = iA_2\Omega_p^* \tag{3a}$$

$$\frac{\partial A_2}{\partial t} = iA_3\Omega_c^* - A_2\left(i\Delta_p + r_2\right) + i\Omega_p \tag{3b}$$

$$\frac{\partial A_3}{\partial t} = iA_2\Omega_c - A_3\left[i\left(\Delta_p + \Delta_c\right) + r_3\right)] \tag{3c}$$

where r_2 and r_3 are added phenomenologically to describe the corresponding decay rates of level |2> and |3>.

In order to correctly describe the propagation of the generated optical solitons in the medium, equations of motion must be simultaneously solved with Maxwell's equation in a self-consistent manner. In the limit of plane waves and slowly varying amplitude approximations, the amplitude of the pulsed laser field $E_p = E_p(z,t)$ obeys Maxwell's equation. Making full use of the polarization amplitude $P(\omega_p) = ND_{21}A_2A_1^*$ with N being the number density of carriers in the conduction band of the MQWs and Rabi frequency $\Omega_p = D_{21}E_P/2\hbar$, we can obtain the equation of motion for Ω_p

$$\frac{\partial\Omega_p}{\partial z} + \frac{1}{c}\frac{\partial\Omega_p}{\partial t} = iK_{12}A_2A_1^* \tag{4}$$

where $K_{12} = 2N\omega_p|D_{12}|^2/(\hbar c)$, c is the speed of light in vacuum. We assume that $A_j = \Sigma_k A_j^{(k)}$, where $A_j^{(k)}$ is the *k*th-order part of A_j in terms of Ω_p. Within an adiabatic framework it can be shown that $A_1^{(1)} = 0$ and $A_j^{(0)} = \delta_{j1}$ (δ_{j1} is the Kronecker δ symbol). Taking the time Fourier transform of Eqs. (3a), (3b), (3c) and (4) and keeping up to the first order of Ω_p, we have

$$\beta_2^{(1)}\left(\Delta_p - \omega - ir_2\right) - \Lambda_p - \beta_3^{(1)}\Omega_c^* = 0 \tag{5a}$$

$$\beta_3^{(1)}\left[\left(\Delta_p + \Delta_c\right) - ir_3 - \omega\right] - \beta_2^{(1)}\Omega_c = 0 \tag{5b}$$

$$\frac{\partial\Lambda_p}{\partial z} - i\frac{\omega}{c}\Lambda_p = iK_{12}\beta_2^{(1)} \tag{5c}$$

$$A_j = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}\beta_j(\omega)\exp(-i\omega t)d\omega \quad j = 2,\ 3 \tag{5d}$$

$$\Omega_p = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}\Lambda_p(\omega)\exp(-i\omega t)d\omega \tag{5e}$$

where $\beta_j^{(1)}$ and Λ_p are the Fourier transforms of $A_j^{(1)}$ and Ω_p, respectively, and ω is the Fourier-transform variable.