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Enhanced index and negative dispersion without absorption in semiconductor quantum wells

Zhiping Wang*, Shenglai Zhen, Xuqiang Wu, Jun Zhu, Zhigang Cao, Benli Yu

Key Laboratory of Opto-Electronic Information Acquisition and Manipulation of Ministry of Education, Anhui University, Hefei 230601, China

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ABSTRACT

We investigate the dispersive and absorptive properties in a three-level ladder-type SQW system that both cascade transitions are driven by the same strong coherent field and are probed by the same weak probe field. It is found that the positive or negative refractive index with vanishing absorption can be also easily obtained in this solid-state system. Our scheme shows many intrinsic characteristics that other schemes do not have, which may provide some possibilities for the technological applications in solid-state optoelectronics.

1. Introduction

It is well known that quantum coherence and interference can give rise to some interesting phenomena, such as electromagnetically induced transparency (EIT) [1–4], enhancing Kerr nonlinearity [5], efficient four-wave mixing [6–8], ultraslow optical solitons [9,10] and so on. Based on atomic coherence and quantum interference, many schemes have been proposed for refractive index enhancement without absorption in atomic media. For example, in 1991, Scully showed that one can use quantum interference to engineer enhanced indices of refraction with simultaneously vanishing absorption in a three-level system [11]. Harris proposed how to reduce the refractive index of a probe beam to unity in a far-off resonant system in an EIT-like manner [12], and later Scully and colleagues presented a proof-of-principle experiment demonstrating a resonant enhancement of the index of refraction accompanied by vanishing absorption in a cell containing a coherently prepared Rb vapor [13]. The results are in good agreement with detailed theoretical predictions [14,15]. In a recent paper, Yavuz demonstrated a scheme where a laser beam which is very far detuned from an atomic resonance experiences a large index of refraction with vanishing absorption [16]. Later on, he and his coworkers experimentally investigated an index-enhancement scheme in a two-photon Raman configuration in an atomic vapor, by utilizing the interference of two Raman resonances, they found that the refractive index of a laser beam that is very far detuned from an electronic resonance can be enhanced while maintaining vanishing absorption [17]. Quite recently, Sagona-Stophel et al. present a five-level atomic system in which the index of refraction of a probe laser can be enhanced or reduced below unity with vanishing absorption in the region between pairs of absorption and gain lines formed by dressing of the atoms with a control laser and rf/microwave fields [18]. By controlling the population distribution in dressed interacting ground states, large robust enhancements of n with vanishing absorption can be achieved.

On the other hand, similar phenomena based on the quantum interference and coherence in the semiconductor quantum wells (SQWs) have also been extensively studied in recent years, such as gain without inversion [19–21], electromagnetically induced transparency [22,23], coherent population trapping [24,25], enhanced index of refraction [26], ultrafast all optical switching [27], Kerr nonlinearity [28] and other novel phenomena [29–38]. The reason for this is mainly the phenomena in the SQWs have many potentially important applications in solid-state optoelectronics. Otherwise, the devices based on intersubband transitions in the SQWs have many inherent advantages that the atomic systems do not have, such as the large electric dipole moments due to the small effective electron mass, the great flexibilities in devices design by choosing the materials and structure dimensions, the high nonlinear optical coefficients. Furthermore, the transition energies, the dipoles, and the symmetries can also be engineered as desired.

In this work, we investigate the dispersive and absorptive properties in a three-level ladder-type SQW system. Our study and the system are mainly based on Refs. [11–18,31,32], however, our results are different from those works. First, we are interested in studying the controllability of the dispersive and absorptive properties in a SQWs system that both cascade transitions are driven by the same strong coherent field and are probed by the

* Corresponding author.
E-mail address: wzping@mail.ustc.edu.cn (Z. Wang).

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same weak probe field, which is much more practical than its atomic counterpart due to its flexible design and controllable quantum-interference effect. Second, the positive or negative refractive index with vanishing absorption can be easily obtained in this semiconductor quantum well system. Third, under corresponding conditions, the indices of refraction are large at three different frequencies where the absorption vanishes, and the whole absorption spectrum displays three pairs of absorption peaks and three pairs of gain (negative absorption) peaks. To our knowledge, there has been no report on these characteristic features of driven three-level SQW system in this cascade configuration. Our paper is organized as follows: in Section 2, we present the theoretical model and establish the corresponding dynamic equations. Our numerical results and physical analysis are shown in Section 3. In Section 4, some simple conclusions are given.

2. Model and dynamic equations

We consider a three-level ladder-type quantum well system with three levels as shown in Fig. 1. Two laser fields $E = 1/2[E_c \exp(-i\omega_c t) + E_p \exp(-i\omega_p t) + c.c.]$ are mediated, of which E_c is a control laser field and serves as coherent driving with Rabi frequencies $\Omega_{c1} = \mu_{12}E_c/\hbar$ and $\Omega_{c2} = \mu_{23}E_c/\hbar$, and E_p is a weak field and is used as a probe field with Rabi frequencies $\Omega_{p1} = \mu_{12}E_p/\hbar$ and $\Omega_{p2} = \mu_{23}E_p/\hbar$. Under the rotating-wave approximations, the Hamiltonian of the system is given by

$$H = H_p + H_c, \tag{1}$$

$$H_p = -\frac{\hbar}{2}e^{-i\delta t}(\Omega_{p1}|1\rangle\langle 2| + \Omega_{p2}|2\rangle\langle 3|) - \frac{\hbar}{2}e^{i\delta t}(\Omega_{p1}^*|2\rangle\langle 1| + \Omega_{p2}^*|3\rangle\langle 2|), \tag{2}$$

$$H_c = \hbar\Delta_2|2\rangle\langle 2| + \hbar(\Delta_1 + \Delta_2)|1\rangle\langle 1| - \frac{\hbar}{2}(\Omega_{c1}|1\rangle\langle 2| + \Omega_{c1}^*|2\rangle\langle 1|) - \frac{\hbar}{2}(\Omega_{c2}|2\rangle\langle 3| + \Omega_{c2}^*|3\rangle\langle 2|), \tag{3}$$

where $\Delta_1 = \omega_{12} - \omega_c$, $\Delta_2 = \omega_{23} - \omega_c$, and $\delta = \omega_p - \omega_c$ are the detunings.

By adopting the standard approach and eliminating ρ_{11} through the population conservation rule for the closed system $\rho_{11} + \rho_{22} + \rho_{33} = 1$, we obtain

$$\frac{\partial\rho_{22}}{\partial t} = \frac{i}{2}\Omega_2\rho_{32} - \frac{i}{2}\Omega_2^*\rho_{23} + \frac{i}{2}\Omega_1^*\rho_{12} - \frac{i}{2}\Omega_1\rho_{12}^* - \gamma_{12}\rho_{33} - (\gamma_{23} + \gamma_{12})\rho_{22} + \gamma_{12}, \tag{4}$$

$$\frac{\partial\rho_{33}}{\partial t} = \frac{i}{2}\Omega_2^*\rho_{23} - \frac{i}{2}\Omega_2\rho_{32} - \gamma_{13}\rho_{33} + (\gamma_{23} - \gamma_{13})\rho_{22} + \gamma_{13}, \tag{5}$$

$$\frac{\partial\rho_{12}}{\partial t} = \frac{i}{2}\Omega_1(2\rho_{22} + \rho_{33} - 1) - \frac{i}{2}\Omega_2^*\rho_{13} - \left(i\Delta_1 + \frac{\Gamma_{12}}{2}\right)\rho_{12}, \tag{6}$$

$$\frac{\partial\rho_{13}}{\partial t} = \frac{i}{2}\Omega_1\rho_{23} - \frac{i}{2}\Omega_2\rho_{12} - \left[i(\Delta_1 + \Delta_2) + \frac{\Gamma_{13}}{2}\right]\rho_{13}, \tag{7}$$

$$\frac{\partial\rho_{23}}{\partial t} = \frac{i}{2}\Omega_2(\rho_{33} - \rho_{22}) + \frac{i}{2}\Omega_1^*\rho_{13} - \left(i\Delta_2 + \frac{\Gamma_{23}}{2}\right)\rho_{23}, \tag{8}$$

$$\frac{\partial\rho_{21}}{\partial t} = -\frac{i}{2}\Omega_1^*(2\rho_{22} + \rho_{33} - 1) + \frac{i}{2}\Omega_2\rho_{31} - \left(\frac{\Gamma_{12}}{2} - i\Delta_1\right)\rho_{21}, \tag{9}$$

$$\frac{\partial\rho_{31}}{\partial t} = -\frac{i}{2}\Omega_1^*\rho_{32} + \frac{i}{2}\Omega_2^*\rho_{21} - \left[\frac{\Gamma_{13}}{2} - i(\Delta_1 + \Delta_2)\right]\rho_{31}, \tag{10}$$

$$\frac{\partial\rho_{32}}{\partial t} = -\frac{i}{2}\Omega_2^*(\rho_{33} - \rho_{22}) - \frac{i}{2}\Omega_1\rho_{31} - \left(\frac{\Gamma_{23}}{2} - i\Delta_2\right)\rho_{32}, \tag{11}$$

where $\Omega_k = \Omega_{ck} + \Omega_{pk}e^{-i\delta t}$ $(k = 1, 2)$ and $\rho_{nm} = \rho_{mn}^*$ $(m, n = 1, 2, 3)$. The population decay rates and dephasing decay rates are added phenomenologically in the above equations [29]. The population decay rates for subband $|i\rangle$, denoted by γ_{ij} $(i \neq j)$, are primarily due to longitudinal optical (LO) phonon emission events at low temperature. The total decay rates Γ_{ij} $(i \neq j)$ are given by $\Gamma_{12} = \gamma_{12} + \gamma_{13} + \gamma_{23} + \gamma_{12}^{dph}$, $\Gamma_{13} = \gamma_{12} + \gamma_{13} + \gamma_{13}^{dph}$ and $\Gamma_{23} = \gamma_{23} + \gamma_{23}^{dph}$, where γ_{ij}^{dph} determined by electron–electron, interface roughness, and phonon scattering processes, is the dephasing decay rate of the quantum coherence of the $|i\rangle \leftrightarrow |j\rangle$ transition.

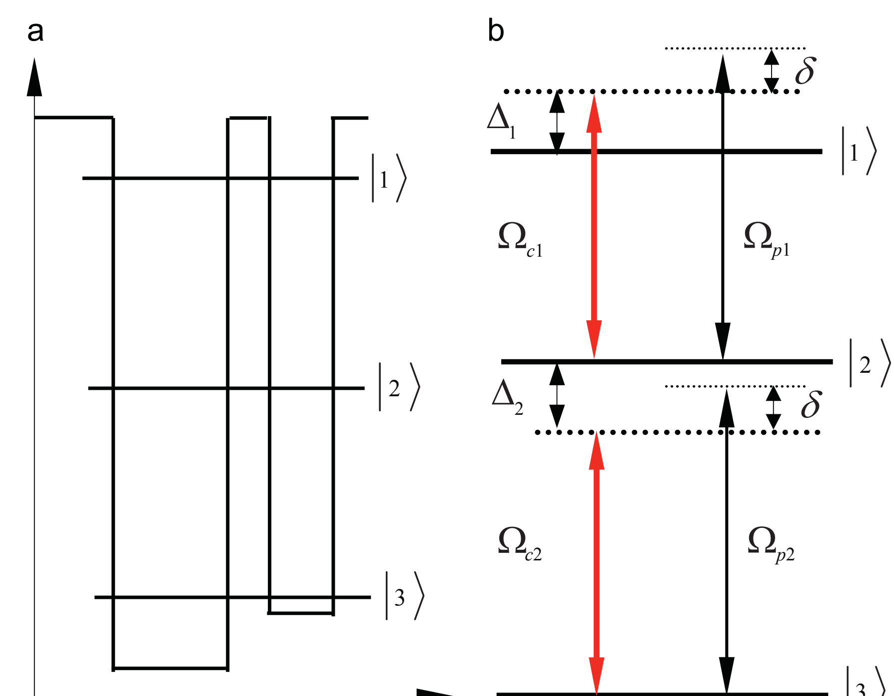

Fig. 1. (a) Schematic diagram of the three-level ladder-type quantum well system. (b) Schematic of the energy level arrangement for the three-level ladder-type quantum well under study.