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Switching feature of EIT-based slow light giant phase-sensitive Kerr nonlinearity in a semiconductor quantum well

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ABSTRACT

A four level inverted Y-type quantum well semiconductor is proposed based on phase-sensitive Kerr nonlinearity with a closed-loop configuration. It is found that as the Rabi-frequency of coupling field increases, the maximal Kerr nonlinearity intensifies and at the same time the probe linear and nonlinear absorption decreases at Telecom wavelength $\lambda = 1550$ nm. The impact of an incoherent pumping field as well as the relative phase of the applied fields on nonlinear optical properties of the QW medium is then discussed. The temporal behavior of the Kerr nonlinearity and the required switching time for switching the nonlinear dispersion are also discussed. The results may be useful for understanding the switching feature of EIT-based slow light Kerr nonlinearity enhancement systems and have potential application in optical information processing and transmission.

1. Introduction

In the few past decades, electromagnetically induced transparency (EIT) [1,2], which results from quantum coherence and interference, has attracted lots of attention in coherent media. In fact, atomic coherence and quantum interference can lead to some interesting phenomena, like superluminal and subluminal propagation of light [3], four-wave mixing (FWM) [4,5], atom localization [6–8], optical soliton [9], optical bistability (OB) [10–13], giant Kerr nonlinearity [14–19], and so on [20–25].

Third order Kerr nonlinearity plays an important role in nonlinear optics with applications in optical shutters [26] to the generation of optical solitons [27,28], quantum nondemolition measurements [29], and quantum teleportation [30]. As a matter of fact, it is favorable to have large Kerr nonlinearities under conditions of low light power and high sensitivities. [31] This requires that the linear susceptibilities should be as small as possible for all pump and absorption losses. In recent years, third-order nonlinear susceptibility with reduced absorption in gases media has been one of the most extensively studied phenomena. For instance, Jiang et al. [16] have explored the effect of spontaneously generated coherence (SGC) on Kerr nonlinearity of a four-level N-type system, and found that the Kerr nonlinearity can be obviously enhanced with SGC mechanism. Niu and Gong [18] investigated the behavior or refractive part of third order susceptibility in general three level atomics systems (Λ, V, and Ladder). They showed that in the Λ and ladder-type systems, the maximal Kerr nonlinearity increases and at the same time enters the electromagnetically induced transparency window as the spontaneously generated coherence intensifies. As for the V-type system, the absorption property is significantly modified and therefore enhanced Kerr nonlinearity without absorption occurs for certain probe detunings.

On the other hand, the study on optical properties of semiconductor quantum well (QW) and quantum dot (QD) nanostructures have attracted considerable attention [32–36]. Due to view point of practical purposes, it is more advantageous to achieve possible solid-state media that could permit to realize the giant Kerr nonlinearities with low pump power and low absorptions. In the conduction band of semiconductor quantum wells (QWs), the two-dimensional electron gas behaves atomic-like optical responses. Quantum interference and coherence in QWs can also produce some interesting phenomena such as strong EIT [37], CPT, [38] LWI, [39] enhancement of refractive index, [40] optical bistability [41–43], Kerr nonlinearity [44–46] and so on [47,48].

The enhancement of Kerr nonlinearities in an asymmetric coupled double quantum-well by analyzing the nonlinear optical response was reported by Yang and colleagues [45]. The effect of Fano-interference on enhancement of the Kerr nonlinearity in an asymmetric GaAs double quantum well is also studied [46].

Recently, the hybrid absorptive–dispersive optical bistability and multistability, [41] as well as the features of two-photon absorption [49], have been reported theoretically in a

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four-levelinverted-Y quantum well system. However, the Kerr nonlinearity behavior of this semiconductor QW is not still reported, which motivates us for the presented work. In this paper, we discuss the possible giant Kerr nonlinearities in subluminal light propagation condition and with reduced probe absorption. The effect of different system parameters on third order nonlinearity is investigated. It is found that increasing coupling field Rabi-frequency provides large Kerr nonlinearity accompanied with EIT condition. In addition, we showed that Kerr nonlinear behavior is strongly dependent on relative phase between applied fields. The effect of an incoherent pump field on linear and nonlinear response of inverted Y-shaped QW nanostructure is then discussed. Finally, the switching optical process for achieving enhanced or reduced Kerr nonlinearity is presented.

2. Models and equation

Consider a four-level inverted-Y quantum well system with four levels as shown in Fig. 1. The quantum well sample considered here could be very much similar to the one used in Refs. [41,49,50].

It is feasible to choose the proper parametric conditions for this QW sample. For instance, the sample can be designed to have transition energies in the range of 120–170 meV and desired dipole moments, and these quantum well samples can be grown by the molecular-beam epitaxy (MBE) method with 40–80 symmetric 10 nm n-doped ($n_e = 6 \times 10^{11}\,\mathrm{cm}^{-2}$)$In_xGa_{1-x}As$($x = 0.47$)wells and 10 nm $Al_yIn_{1-y}As$($y = 0.48$) barriers supported on a lattice-matched undoped InP substrate containing a 1–2 mm diameter etched hole for optical access [50].

Transition $|2\rangle \leftrightarrow |1\rangle$ is mediated with a weak tunable probe field E_p with frequency ω_p. Also, a coupling field of frequency ω_c and phase φ_c is applied to transition $|2\rangle \leftrightarrow |4\rangle$, while a pumping field with frequency and phase ω_2 and φ_2 is applied to $|3\rangle \leftrightarrow |2\rangle$. In addition, a cycling field E_d, with frequency ω_d and phase φ_d couples levels $|4\rangle$ and $|1\rangle$. The corresponding Rabi-frequencies are defined as $\Omega_p = \vec{E}_p.\,\vec{\wp}_{21}/2\hbar$, $\Omega_d = \vec{E}_d.\,\vec{\wp}_{41}/2\hbar$, $\Omega_c = \vec{E}_c.\,\vec{\wp}_{24}/2\hbar$ and $\Omega_2 = \vec{E}_2.\,\vec{\wp}_{32}/2\hbar$, where $\vec{\wp}_{ij}$ denotes the induced electric dipole moment of $|i\rangle \leftrightarrow |j\rangle$ transition.

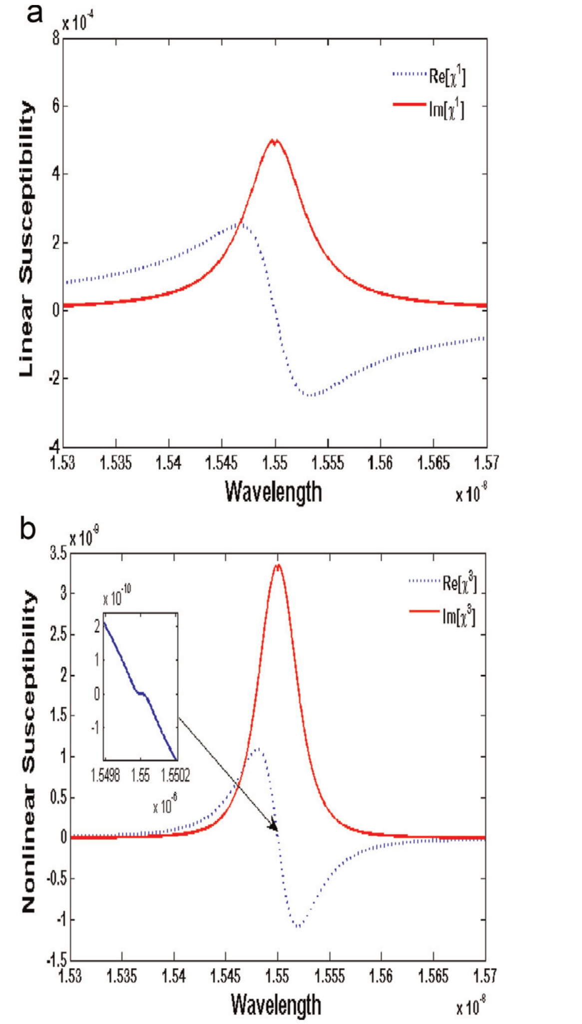

Fig. 2. Linear and nonlinear susceptibilities versus probe field wavelength. (a) Linear absorption (solid line), and linear dispersion (dot line). (b) Nonlinear absorption (solid line), and Kerr nonlinearity (dot line). The selected parameters are: $\gamma_1 = 1$ THz, $\gamma_3 = \gamma_2 = \gamma_1$, $\gamma_4 = 0.04\,\gamma_1$, $r = 0$, $\Omega_p = 0.001\,\gamma_1$, $\Delta_c = 0$, $\Delta_2 = 0$, $\Delta_d = 0$,. $\Omega_c = 0.02\,\gamma_1$, $\Omega_2 = 0.05\,\gamma_1$, $\Omega_d = 0.01\,\gamma_1$, $\phi = \pi/2$.

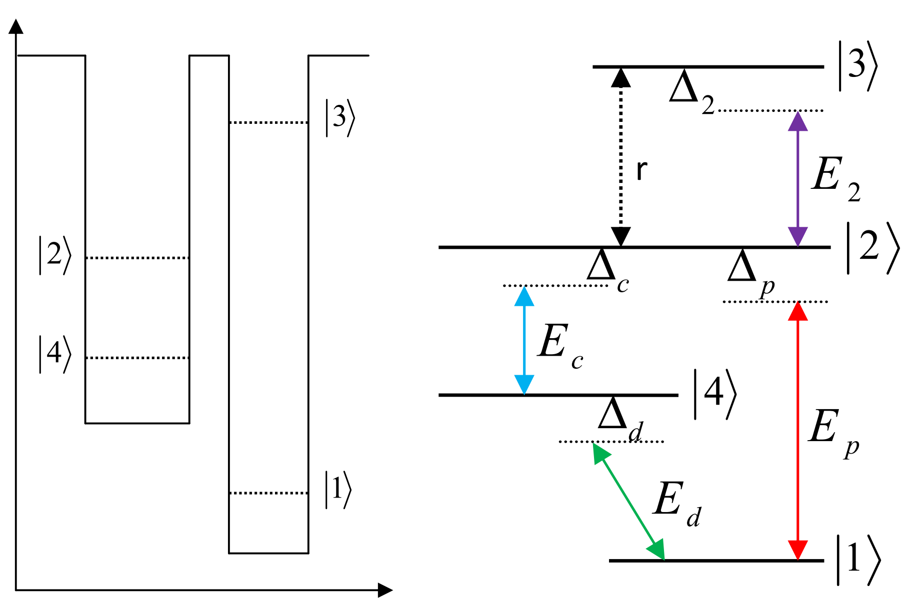

Fig. 1. (a) Schematic diagram of the four-level inverted-Y quantum well system. (b) Schematic of the energy level arrangement for the quantum well system under study.