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Tunneling-induced enhancement of self-Kerr nonlinearity in asymmetric quantum wells

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ABSTRACT

We propose an asymmetric AlGaAs/GaAs double quantum wells (QWs) structure for realizing the enhancement of self-Kerr nonlinearity. It is found, with resonant tunneling, that the self-Kerr nonlinearity can be clearly enhanced, while the absorption of probe field is very small and can be safely neglected. We attribute the enhancement of self-Kerr nonlinearity mainly to the constructive interference induced by resonant tunneling.

1. Introduction

Kerr nonlinearity, which corresponds to the refractive part of the third-order susceptibility, plays an important role in the field of nonlinear optics. It is desirable to achieve giant Kerr nonlinearity with low light powers [1]. Over the past decades, there has been a growing interest in techniques that achieve significant Kerr nonlinearity [2]. These schemes are exciting and important because of both practical and fundamental reasons. Key practical applications include all-optical switches that can operate at an energy cost of a single photon, two-qubit quantum gates between two single photons [3,4] and generation of optical solitons [5]. Harris and co-workers have introduced the idea of electromagnetically induced transparency (EIT) [2], which allows controlled manipulations of the optical properties of atom or atom-like media and hence leads to suppression of linear absorption and enhancement of nonlinear susceptibility [6]. This means that EIT-based enhancement of Kerr nonlinearity is hopefully possible to be obtained by eliminating absorption. Giant Kerr nonlinearity in EIT media has been the focus of several recent studies theoretically [7–10] and experimentally [11,12]. Schmidt et al. proposed a four-level N-configuration system to enhance the Kerr nonlinearity where the ideal EIT regime is disturbed by an additional off-resonant level [7]. Subsequently, the idea of enhancement of Kerr nonlinearity via multilevel atomic coherence was proposed [8], where one-photon resonant absorption is suppressed by destructive coherence effects. In a generic four-level system, coherence perturbation leads to double-dark resonance, which as a whole is the definite signature of a new type of quantum interference effect [13]. The interaction of double dark resonances can enhance the self-Kerr nonlinearity almost several orders of magnitude accompanied by vanishing linear absorption [9]. In general three-level systems (Λ type, ladder type and V type), the spontaneous emission interference induces an extra coherence and therefore gives rise to the enhancement of Kerr nonlinearity [10].

In the conduction band of semiconductor quantum wells (QWs) structure, owing to the quantum coherence induced by laser [14], the confined electron gas exhibits atomiclike properties. Different from atomic system, the advantages of semiconductor QWs structure such as large electric dipole momentums, controllable intersubband energies and the electron function symmetries create the opportunities of building opto-electron devices that harness atom physics. There is great interest in extending the study of quantum interference phenomena from atomic medium to semiconductor QWs structure. In the coming years, there has been a fast growth of research activity aimed at studying the quantum interference effects in semiconductors nanostructures [15–38]. For examples, the strong EIT [15], lasing without inversion (LWI) [16], tunneling induced transparency (TIT) [17], ultrafast optical switching via Fano interference [18], ultraslow optical solitons [19,20], tunneling-induced enhancement of Kerr nonlinearity [21,22], highly efficient four-wave mixing (FWM) process [23–26], and so on. By using the Stark shift induced by Fano interference, the enhancement of self-Kerr nonlinearity can be realized with canceled absorptions [27]. More recently, driving two QWs subbands by two rectangular shape electromagnetic fields, Kosionis et al. demonstrated

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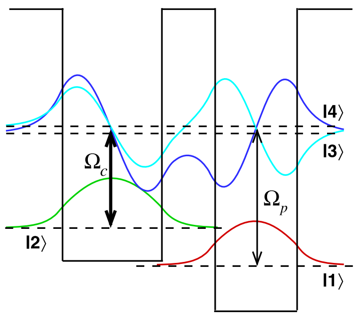

Fig. 1. (Color online.) Conduction subband of the QWs in dressed state picture. The ground subbands of the deep well $|1\rangle$ and the shallow one $|2\rangle$ are, respectively, coupled to the excited subbands $|3\rangle$ and $|4\rangle$ near resonantly via the probe and coupling fields.

that nonabsorptive Kerr nonlinearity can be obtained by controlling the electron sheet density and the intensity of the pump field [28].

In our previous work, we have demonstrated the idea of the tunneling-induced large cross-Kerr nonlinearity in an asymmetric double AlGaAs/GaAs QWs structure with a continuum [21]. Resonant tunneling exhibits constructive interference in cross-Kerr nonlinearity, large cross-Kerr nonlinearity could be achieved, while the absorption is canceled due to TIT. More recently, strongly interacting photons with ultraslow group velocity also has been realized owning to resonant tunneling in an asymmetric QWs [22]. In QWs structure, the presence of resonant tunneling can modify the optical responses dramatically. It induces not only transparency, but also the enhancement of Kerr nonlinearity (XPM) [21,22] and the efficiency of FWM [26]. Thus, the natural question is whether resonant tunneling can induce enhancement of self-Kerr nonlinearity with vanishing absorption. In the present Letter, we design an asymmetric AlGaAs/GaAs double QWs to address this question. Our calculations show that resonant tunneling exhibits constructive interference in self-Kerr nonlinearity. By combining this constructive interference with the advantages of three-level Λ-type configuration, the tunneling-induced enhancement of self-Kerr nonlinearity can be realized, while the absorption is canceled and can be ignored due to the destructive interference between different transition channels.

2. Structure and equations

We investigate an n-doped asymmetric AlGaAs/GaAs double QWs structure, whose relevant conduction subbands and wave functions in dressed state picture are shown in Fig. 1. The left shallow well and right deep well are, respectively, made up of an $Al_{0.06}Ga_{0.94}As$ layer with thickness of 8.8 nm and a 7.4 nm GaAs layer, and they separated by a 4.6 nm $Al_{0.4}Ga_{0.6}As$ potential barrier. The components of the potential barriers on both sides are the same as that of the central potential barrier. By solving the effective mass Schrödinger equations, four conduction subbands would be observed. The eigenenergies of two ground subbands are $E_1 \approx 49.4$ meV (the right deep well $|1\rangle$) and $E_2 \approx 89.1$ meV (the left shallow well $|2\rangle$), respectively. Two closely spaced delocalized upper subbands $|3\rangle$ and $|4\rangle$ with eigenenergies $E_3 \approx 190.0$ meV and $E_4 \approx 196.5$ meV are created by mixing the first excited subbands of the left shallow well ($|se\rangle$) and the right deep well ($|de\rangle$) by tunneling, i.e., $|3\rangle = (|se\rangle - |de\rangle)/\sqrt{2}$ and $|4\rangle = (|se\rangle + |de\rangle)/\sqrt{2}$. The solid curves denote the corresponding wave functions. A weak probe field with the central frequency ω_p couples the ground subband $|1\rangle$ to the excited subbands $|3\rangle$ and $|4\rangle$, while the control field with central frequency ω_c couples the intermediate subband $|2\rangle$ with two excited subbands.

Under the dipole approximation and rotating-wave approximation (RWA), the electron dynamics can be described using equations of motion for probability amplitudes $b_i(t)$ $(i = 1-4)$ of the states

$$\dot{b}_1 = i\Omega_p(b_3 + kb_4), \tag{1}$$

$$\dot{b}_2 = id_2b_2 + i\Omega_c(b_3 + qb_4), \tag{2}$$

$$\dot{b}_3 = id_3b_3 + i\Omega_pb_1 + i\Omega_cb_2, \tag{3}$$

$$\dot{b}_4 = id_4b_4 + ik\Omega_pb_1 + iq\Omega_cb_2, \tag{4}$$

where $\Delta_1 = \omega_p - (\omega_3 - \omega_1)$ and $\Delta_2 = \omega_c - (\omega_3 - \omega_2)$ are the detunings with ω_j $(j = 1–4)$ being the eigenfrequency of the subband $|j\rangle$. As usual, we assume one half of the Rabi frequencies of the probe and control fields $\Omega_p = \mu_{31}E_p/2\hbar$ and $\Omega_c = \mu_{32}E_c/2\hbar$ are real with μ_{31} and μ_{32} being corresponding dipole matrix elements. As in the experiments in Refs. [17,36], we consider transverse magnetic (TM) polarized fields incident at an angle of 45 degrees with respect to the growth axis so that all transition dipole moments include a factor $1/\sqrt{2}$ as intersubband transitions are polarized along the growth axis. $q = \mu_{42}/\mu_{32}$ and $k = \mu_{41}/\mu_{31}$ present the ratios between the relevant subband transition dipole moments. For the QWs structure under consideration, they are turn out to be $q \approx 0.89$ and $k \approx -1.04$. E_p and E_c are, respectively, the slowly varying electric field amplitudes of the probe and coupling fields. $d_2 = \Delta_2 - \Delta_1 + i\gamma_2$, $d_3 = \Delta_1 + i\gamma_3$, $d_4 = \Delta_1 - \delta + i\gamma_4$, and δ is defined by $\delta = \omega_4 - \omega_3$. γ_i $(i = 2–4)$ is the electron decay rate, which are introduced to account not only for intrasubband phonon scattering and electron–electron scattering but also for inhomogeneous broadening due to scattering on interface roughness.

3. Results and discussion

Our purpose is to investigate the feasibility of enhancing the self-Kerr nonlinearity by using resonant tunneling, and inhibiting the absorption simultaneously. We therefore focus our attention on the susceptibility, which is defined as [4]

$$\chi = \frac{N\mu_{13}}{\varepsilon_0 E_p}\left(b_3^{ss} + kb_4^{ss}\right)b_1^{ss} = \frac{N|\mu_{13}|^2}{2\hbar\varepsilon_0\Omega_p}\left(b_3^{ss} + kb_4^{ss}\right)b_1^{ss}. \tag{5}$$

Here N is the electron volume density, and b_j^{ss} $(j = 1, 3, 4)$ is the steady state amplitude b_j. In order to obtain the expressions of b_j, we consider the situation that the electron is initially prepared in the ground subbands $|1\rangle$, and assume the probe field is very comparatively weak ($\Omega_p \ll \Omega_c$, Δ_1, Δ_2, δ) such that the electronic ground subband $|1\rangle$ is not depleted, i.e., $b_1 \approx 1$. Under these assumptions and following the standard processes [4], one immediately obtains the following expression for the steady state amplitudes

$$b_2^{ss} = \frac{b_1^{ss}}{\mathcal{Z}}(d_4 + kqd_3)\Omega_c\Omega_p, \tag{6}$$

$$b_3^{ss} = \frac{b_1^{ss}}{\mathcal{Z}}\left[d_2d_4 + (k - q)q\Omega_c^2\right]\Omega_p, \tag{7}$$

$$b_4^{ss} = \frac{b_1^{ss}}{\mathcal{Z}}\left[kd_2d_3 - (k - q)\Omega_c^2\right]\Omega_p. \tag{8}$$

Here, $\mathcal{Z} = d_2d_3d_4 - (d_4 + q^2d_3)\Omega_c^2$. The expression of b_1^{ss} can be obtain by combining the results above with the condition $\sum_{i=1}^{4}|b_i^{ss}|^2 = 1$. Inserting these results into Eq. (5) and expanding in series at the lowest orders in the probe electric field E_p, one gets

$$\chi = \chi^{(1)} + \chi^{(3)}|E_p|^2, \tag{9}$$