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Dynamic propagation study of phase-controlled infrared-light pulses in low-dimensional semiconductor heterostructures

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ABSTRACT

We study the propagation effects of the phase-controlled infrared-light pulses in semiconductor quantum-well (QW) heterostructures under realistic experimental conditions. By numerically solving the coupled Bloch–Maxwell equations for electrons and fields simultaneously on numerical grids in time and space, we show that the propagation dynamics can be dramatically modified by varying the relative phase of the applied fields. This opens up the possibility to study optimal control of light propagation in the QW solid materials.

1. Introduction

In the past few decades, the coherent control of light-matter interaction has attracted great interest and has been well studied due to its wide applications in diverse domains, especially with the method of laser induced quantum coherence and interference [1–4]. Coherent laser-driven, three-level (such as Λ-type [5], Ξ-type [6], V-type [7], Δ-type [8–14], ...) atoms and multi-level (such as Y-type or inverted-Y-type [15–18], N-type [19,20], tripod-type [21–23], ...) atoms, instead of two-level atoms, are widely used to study a variety of new quantum optical phenomena in which the behaviors of a weak probe laser field can be efficiently controlled by additional strong control laser fields without considering the propagation effects. One of the most important behaviors is the modification of the absorption, dispersion, and nonlinearity of the system due to quantum coherence and interference effects, such as electromagnetically induced transparency (EIT) [5,6,24].

On the other hand, it has been understood over the past few years that semiconductor quantum wells (QWs) can be quite useful in the topical area of nanophotonics [25]. The main advantages of solid QWs over other approaches like cold atom gases are large electric dipole moments due to the small effective electron mass, high nonlinear optical coefficients, a great flexibility in device design by choosing the materials and structure dimensions, and their potential for easy integration. Besides, in semiconductor QW-based devices the transition energies, dipole moments, and symmetries can also be engineered as desired. Several successfully performed experiments have aided the theoretical predictions, for example, gain without inversion [26], optical switching [27], slow light [28–30], tunneling-induced transparency (TIT) [31,32], EIT [33–36], and infrared generation [37], etc. For practical applications, a QW-based solid system would be preferred. In particular, the idea of connecting the quantum coherent control world of the optical response with the ultra-small world of nanosize optical systems like QWs with tailored properties is very promising.

In this Letter, the propagation effects of the phase-controlled infrared-light pulses in a closed-loop three-subband QW system are studied theoretically with realistic parameters which can be

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reached in current experiments. By numerically solving the coupled Bloch–Maxwell equations for electrons and fields simultaneously on numerical grids as functions of time and space, it is found that the propagation dynamics are modified significantly during propagation due to the change of the relative phase of the applied fields. Proper choice of the relative phase could lead to the gain and the loss-free propagation of the weak infrared pulse signal in the QW medium. Compared with previous works on atomic gases, the present work on solid materials may be of interest for the infrared-light amplifier working on quantum coherence effects as far as realistic applications are concerned.

The rest of this Letter is organized into three parts as follows. In Section 2, we establish the physical model under study and derive the coupled Bloch–Maxwell equations describing the interaction of two infrared-light pulse signals with such a closed-loop three-subband QW system. In Section 3, we analyze and discuss dynamical propagation behaviors of phase-controlled infrared-light pulse signals via numerical simulations. Finally, our main conclusions are summarized in Section 4.

2. Theoretical framework and basic equations for a closed-loop three-subband QW system

As shown in Fig. 1, we consider an asymmetric QW structure (e.g., a rectangular well with different barrier heights) with three energy levels: one lowest-lying heavy-hole level and two electron levels. The red lines indicate the confinement potential consisting of conduction-band potential and valence-band potential for electron (top) and hole (bottom). The blue lines represent two electron levels (upper) and one heavy-hole level (lower). All possible transitions are dipole allowed because of the QW asymmetry who breaks the parity of the wave functions [38,39]. This asymmetry can be induced by a dc field or by a small change to the composition of the QW. The energy differences of the interband (IB) transitions $|1\rangle \leftrightarrow |2\rangle$, $|1\rangle \leftrightarrow |3\rangle$ and the intersubband (ISB) transition $|2\rangle \leftrightarrow |3\rangle$ are ω_{21}, ω_{31}, and ω_{32} ($\omega_{31} = \omega_{21} + \omega_{32}$), respectively. For more details on this QW system we refer the reader to Ref. [37]. The QW system under consideration interacts with one continuous-wave (cw) pump laser (central frequency ω_L and initial phase ϕ_L) and two infrared pulse signals (central frequencies ω_p, ω_c and initial phases ϕ_p, ϕ_c). In the present analysis we use the following method: the semiconductor QW with low doping is designed such that electron–electron effects have very small influence in our results. As a result, many body effects arising from electron–electron interactions are not included in our study. This method has described quantitatively the results of several experimental papers [26,31,32,36,40] and has been used in several theoretical papers [27,30,37–39].

Using this configuration and under the rotating-wave approximation (RWA), with the assumption of $\hbar = 1$, the resulting 3×3 Hamiltonian in the interaction picture can be written in the form

$$\mathcal{H}_{int} = \begin{bmatrix} 0 & -\Omega_c^* & -\Omega_p^* \\ -\Omega_c & \Delta_c & -\Omega_L^* e^{-i\phi} \\ -\Omega_p & -\Omega_L e^{i\phi} & \Delta_p \end{bmatrix}, \qquad (1)$$

where we have taken the ground subband level $|1\rangle$ as the energy origin for the sake of convenience. Ω_n ($n = p, c, L$) are one-half Rabi frequencies for the relevant laser-driven IB and ISB transitions, i.e., $\Omega_p = \mu_{31} E_p/(2\hbar)$, $\Omega_c = \mu_{21} E_c/(2\hbar)$, and $\Omega_L = \mu_{32} E_L/(2\hbar)$, with $\mu_{kl} = \vec{\mu}_{kl} \cdot \vec{e}_L$ denoting the dipole moment for the electronic transition between subbands $|k\rangle$ and $|l\rangle$ ($\vec{e}_L$ is the unit polarization vector of the corresponding laser field). It should be noted that another commonly used definition of the Rabi frequency is: e.g., $\Omega_p = \mu_{31} E_p/\hbar$, which differs by a factor of 2 from the definition used above. The detunings Δ_p, Δ_c and Δ_L are, respectively, given by $\Delta_p = \omega_{31} - \omega_p$, $\Delta_c = \omega_{21} - \omega_c$, and $\Delta_L = \omega_{32} - \omega_L$. The symbol ϕ is the relative phase, it is only relevant to the initial phase of the applied fields and is defined by $\phi = \phi_p - \phi_c - \phi_L$.

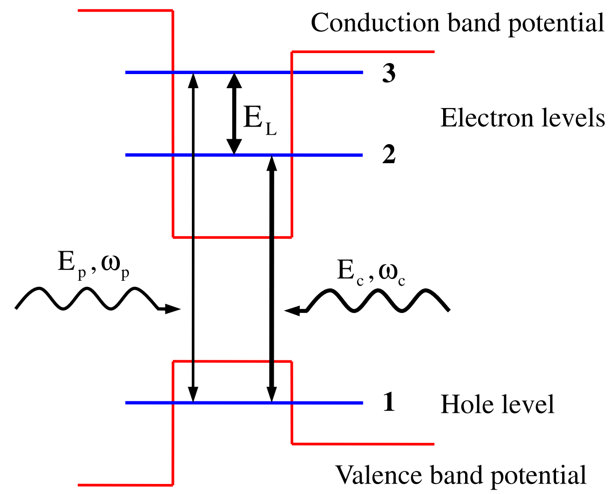

Fig. 1. (Color online.) Energy-band diagram for a closed-loop three-level model in an asymmetric laser-driven QW system. The red lines indicate the confinement potential consisting of conduction-band potential and valence-band potential for electron (top) and hole (bottom). The blue lines indicate two electron levels (denoted as level $|3\rangle$ and level $|2\rangle$) and one heavy-hole level (denoted as level $|1\rangle$). There are three possible optical dipole transitions (frequencies): $|1\rangle \leftrightarrow |2\rangle$ (ω_{21}), $|1\rangle \leftrightarrow |3\rangle$ (ω_{31}), and $|2\rangle \leftrightarrow |3\rangle$ (ω_{32}). The probe and control infrared pulse signals with amplitudes E_p and E_c interact respectively with IB transitions $|1\rangle \leftrightarrow |3\rangle$ and $|1\rangle \leftrightarrow |2\rangle$, while a cw pump laser with amplitude E_L acts on ISB transition $|2\rangle \leftrightarrow |3\rangle$.

Here we would like to illuminate three points as follows:

(i) In the above derivation process of the Hamiltonian operator (1), we have assumed that the central frequencies of these three optical fields satisfy $\omega_p = \omega_c + \omega_L$ for the sake of simplification, thus the relationship $\Delta_p = \Delta_c + \Delta_L$ can be automatically obtained and vice versa. In this regard, all discussions followed is under the condition of resonant excitations, i.e., $\Delta_p = \Delta_c = \Delta_L = 0$.

(ii) It is quite obvious from the general structure of Fig. 1 that two possible pathways from state $|1\rangle$ to state $|3\rangle$ exists: the direct one $|1\rangle \xrightarrow{\Omega_p} |3\rangle$ and the indirect one $|1\rangle \xrightarrow{\Omega_c} |2\rangle \xrightarrow{\Omega_L} |3\rangle$. The role of the relative phase ϕ on the dynamic propagation behavior in such a closed-loop three-level system can be explained from quantum interference induced by these two transition pathways: the total probe absorption or gain amplitude is the sum of two distinct components associated with ϕ_p or $\phi_c + \phi_L$. Accordingly, the dependence of the probe gain on relative phase $\phi = \phi_p - \phi_c - \phi_L$ is the consequence of interference between two competing transition pathways, as will be shown below. As a result, the relative phase ϕ can be used as a control parameter to investigate the features of the light dynamical propagation through the QW medium.

(iii) According to Eq. (1), the relative phase is placed on the cw pump field. In fact, the phase dependence in a closed-loop system can be imparted to anyone of the applied fields. It is evident that the phase dependence would vanish provided that no cw pump field is applied. In order to account for the effect of the relative phase on the dynamical propagation, we will keep the initial phases of the probe and control infrared pulse signals fixed and modulate the initial phase of the pump field.

Using the density-matrix formalism, we begin to describe the electron dynamics of the closed-loop QW system under study. By