



Dynamics and control of few-cycle ultrashort pulse propagation in an asymmetric coupled-quantum-well nanostructure

Jiahua Li^{a,*}, Rong Yu^b, Liugang Si^a, Pei Huang^a, Xiaoxue Yang^a

^a Wuhan National Laboratory for Optoelectronics and School of Physics, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China

^b School of Science, Hubei Province Key Laboratory of Intelligent Robot, Wuhan Institute of Technology, Wuhan 430073, People's Republic of China

ARTICLE INFO

Article history:

Received 9 January 2010

Received in revised form 28 February 2010

Accepted 23 May 2010

Keywords:

Few-cycle ultrashort pulse

Coupled quantum wells (CQWs)

Predictor–corrector algorithm

Finite-difference time-domain method

ABSTRACT

The nonlinear propagation of few-cycle ultrashort pulse in an asymmetric coupled-quantum-well (CQW) nanostructure is simulated by solving numerically the full Maxwell–Bloch equations with an iterative predictor–corrector finite-difference time-domain method. The behaviors of electric field profiles for 2π and 4π ultrashort pulses in different propagating zones are predicted in details beyond the slowly varying envelope and rotating-wave approximations. This investigation may provide a guideline for optimizing and controlling ultrashort pulses in solid-state media, which are promising for practical applications in high-speed optical communications.

© 2010 Elsevier B.V. All rights reserved.

In recent years, the research for the resonant interaction of ultrashort laser pulse with atoms or molecules is an interesting topic in the region of ultrafast optics (see [1] for recent review). Many new physical phenomena including carrier-wave Rabi flopping (RF) [2], carrier-wave reshaping [3–6], soliton pulse formation [7,8], significantly higher spectral components [9–12], and controllable ultrafast optical four-wave mixing [13–15], based on full-wave Maxwell–Bloch equations, have been discovered in gaseous media. For example, a significant influence of the time-derivative driven nonlinearities on the nonlinear evolution of ultrashort laser pulses has been revealed in a two-level atomic system [16]. The formation of optical subcycle pulses has been demonstrated in atomic media of two-level systems due to the pulse splitting and reshaping of few-cycle ultrashort laser pulses [17]. The notion of carrier-wave Rabi flopping in a two-level atom, which is caused by the electric field time-derivative effects, has been first proposed theoretically by Hughes [2] and subsequently demonstrated experimentally in GaAs [18]. Despite the extensive work in this area, as far as we know, for few-cycle ultrashort laser pulses, it has rarely been investigated in the solid-state multilevel media such as semiconductor quantum-well materials.

It has been understood over the past few years that semiconductor quantum wells (QWs) and coupled quantum wells (CQWs) can be quite useful in the topical area of nanophotonics [19–21,23]. The major advantages of QWs/CQWs over other approaches 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/CQW devices the transition energies, dipoles, and symmetries can also be engineered at will. Several successfully performed experiments have aided the theoretical predictions, for instance, coherently controlled photon-current generation [22], gain without inversion [23], tunnelling-induced transparency (TIT) [24,25], optical rectification [26,27], electromagnetically induced transparency (EIT) [28–31], and Rabi oscillations [32–35], etc. For practical applications, a QW/CQW solid system would be preferred.

The finite-difference time-domain and predictor–corrector method has been proven to be one of the most powerful numerical techniques that usefully applied to a wide range of optical devices through solving all components of the electromagnetic field. This method, which can be implemented on a desktop computer, allows for a rigorous and complete treatment of the optical part of the problem. Moreover, it can treat the density matrix directly, complex relaxation functions can be incorporated. However, other approaches have generally been considered too computationally demanding for simulation of ultrashort pulse propagation dynamics. In view of these facts, in this communication we explore dynamical propagation and coherent control of a few-cycle ultrashort laser pulse in an asymmetric CQW system by solving the full Maxwell–Bloch equations with the finite-difference time-domain and predictor–corrector methods. The behaviors of electric field profiles for 2π and 4π ultrashort pulses in different propagating regions are shown clearly under the condition without using the slowly varying envelope and rotating-wave approximations. The proposed CQW scheme for optimizing and controlling ultrashort pulses in solid-state media is much more practical than that in gaseous media as a result of its flexible

* Corresponding author. Tel./fax: +86 2787557477.

E-mail address: huajia_li@163.com (J. Li).

design and the wide adjustable parameters and thus ultrashort pulse control in semiconductor-based devices is very appealing from a more applied point of view.

The asymmetric CQW structure we consider is shown schematically in Fig. 1(a). The red lines indicate the confinement potential consisting of conduction-band potential and valence-band potential for electron (top) and hole (bottom). The two coupled conduction subbands (the upper blue lines) between the wide well and the narrow well are labelled as levels $|2\rangle$ and $|3\rangle$, and the heavy-hole subband (the lower blue line) in the narrow well is denoted as level $|1\rangle$. There are two possible optical dipole transitions (frequencies): $|1\rangle \leftrightarrow |2\rangle$ (ω_2) and $|1\rangle \leftrightarrow |3\rangle$ (ω_3). The CQW sample consists of ten pairs of wide-well and narrow-well regions which are separated by 25-Å-thick $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ barrier. Both wells are made of a GaAs layer with 145 Å for the wide well and 100 Å for the narrow well. The pairs are isolated from each other by 200-Å-wide buffer layers and capped with 3500-Å-thick $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ layers. All regions are undoped except the n-type GaAs substrate. The value of the wavelength at the interband transitions is typically $\lambda \sim 700\text{--}850\text{ nm}$, the value of the dipole matrix element is typically $\langle d \rangle \sim 0.3\text{--}1\text{ nm}$ and the dephasing times of excitons are of the order of the picosecond. For more details on this CQW system we refer the reader to Refs. [36,37]. In the present study, we will just focus on the condition of low temperatures

up to 10 K [37], and the semiconductor CQW samples with low doping are 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 [20,23–25,31,38] and has been used in several theoretical papers [21,39–45]. As a matter of fact, the influences of electron–electron interactions on the dynamics of interband transitions in the CQWs have been investigated in several recent publications, see e.g., Refs. [32–35]. These works have shown that this dynamics can be significantly altered but for much larger electron doping than those of interest here.

We consider dynamic propagation of a linearly polarized few-cycle laser pulse in such a driven CQW medium as shown in Fig. 1(b). We assume that the electric field and magnetic field are polarized along x- and y-axis directions, respectively. Therefore we can represent the electric field E_s and magnetic field H_s by the scalars E_{sx} and H_{sy} , respectively. Based on the one-electron density matrix equations, the time evolution of density matrix about ρ_{ij} ($i, j = 1, 2, 3$) is given by

$$\frac{\partial \rho_{11}}{\partial t} = -i\Omega_s(\rho_{21} - \rho_{12}) - if\Omega_s(\rho_{31} - \rho_{13}), \quad (1a)$$

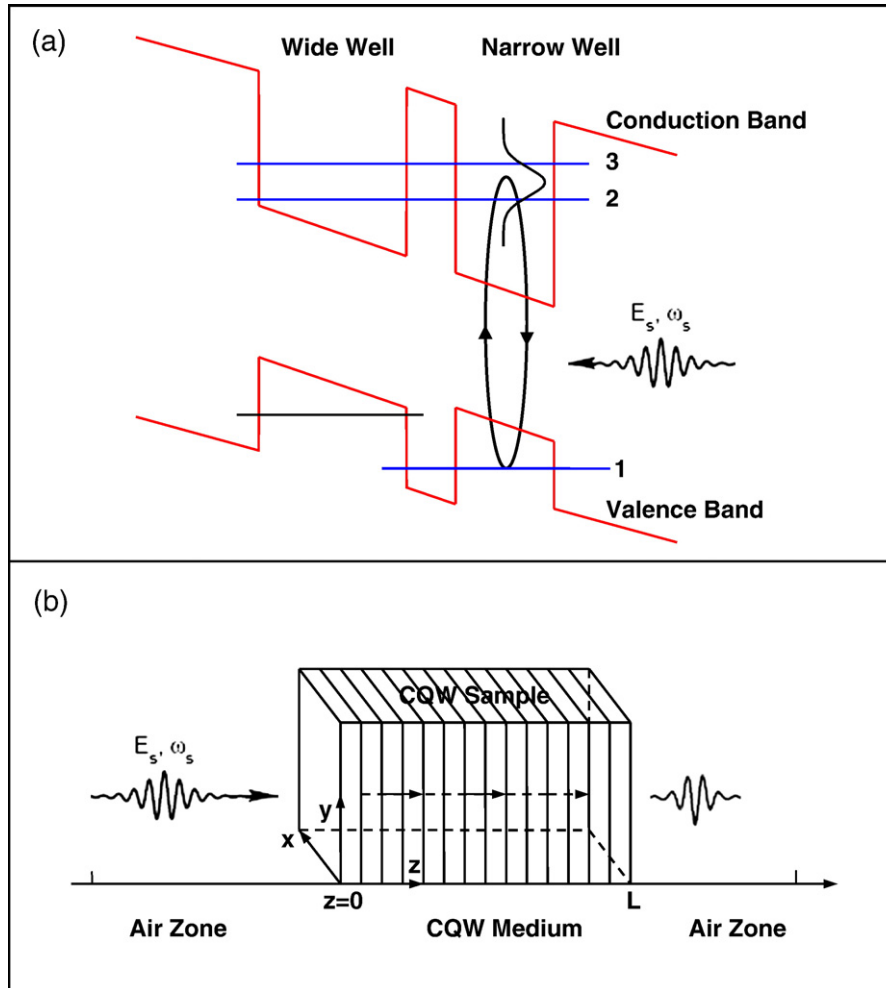


Fig. 1. (a) Energy-band diagram for a three-level model in an asymmetric laser-driven CQW system. The red lines indicate the confinement potential consisting of conduction-band potential and valence-band potential for electron (top) and hole (bottom). The blue lines indicate the two coupled conduction subbands between the narrow well and the wide well (denoted as level $|3\rangle$ and level $|2\rangle$) and the heavy-hole subband in the narrow well (denoted as level $|1\rangle$). A reverse-bias field at about 7 kV/cm [37] can be applied between a semitransparent chromium contact on the sample surface and the n-doped substrate, with higher fields corresponding to the wide well being at a higher electron potential than the narrow well. There are two possible optical dipole transitions (frequencies): $|1\rangle \leftrightarrow |2\rangle$ (ω_2) and $|1\rangle \leftrightarrow |3\rangle$ (ω_3). A few-cycle ultrashort laser pulse with carrier frequency ω_s and amplitude E_s couples simultaneously such two interband transitions $|1\rangle \leftrightarrow |2\rangle$ and $|1\rangle \leftrightarrow |3\rangle$. (b) The schematic diagram of a few-cycle ultrashort laser pulse excitation. The pulse initially propagates in the air zone, and thereafter inject into the medium at $z = 0$. It subsequently propagates through the CQW medium of length L and finally exits into the right air zone at $z = L$.

Download English Version:

<https://daneshyari.com/en/article/1539035>

Download Persian Version:

<https://daneshyari.com/article/1539035>

[Daneshyari.com](https://daneshyari.com)