INTERACTION OF SEMICONDUCTOR LAYERS AND DOT CHAINS WITH THE ELECTROMAGNETIC FIELD

PHD THESIS

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Preliminaries and scientific objectives

The analogy between the dynamics of two level atoms interacting with light and the magnetic resonance phenomenon is well known, the dynamics of both systems are described by the Bloch-equations [1]. If the central frequency of the pulse is in resonance with an atomic transition, and the process is shorter then the relaxation time, then the inversion oscillates periodically. This is the Rabi oscillation. In quantum informatics this effect can be used to manipulate physical quantum bits: two-level systems.

In case of short pulses the usual approximations (slowly varying envelope approximation: SVEA, rotating wave approximation: RWA) are invalid [2]. The limits of these approximations were investigated in the case of atomic systems [3], while until recently the usual approximations have been used in the case of semiconductors [4].

Our aim is to describe the interaction of semiconductor layers and ultrashort pulses. In the model calculations the data of GaAs semiconductor is used as this material is widely used in the semiconductor technology. The problem may be interesting at two frequency ranges: at the polariton resonance in the infrared, and in the optical range of band transitions.

Our aim is the theoretical investigation of the propagation of few optical cycle pulses at the polariton resonance (λ_0=37,31 μm) of the GaAs semiconductor layer. We plan to demonstrate the influence of transient phenomena in the shape of transmitted and reflected pulses.

Beyond the scope of SVEA one expects new phenomena. Hughes [3] predicted the appearance of higher spectral components for two-level atoms. Mücke et. al [5] investigated the interaction of a GaAs semiconductor layer with ultrashort pulses at the resonance of the 1,42 eV band gap. They found a splitting in the third harmonic of the transmitted pulse. The splitting cannot be explained in the framework of SVEA. The experimental team used a simple model to describe the phenomenon. *Our aim is to investigate the theoretical description on the basis of the semiconductor Bloch equations, to consider the propagation effects and to compare our theoretical results with the experimental findings of Ref.* [5].

The development of experimental techniques allowed to grow quantum dots (qdots) on the surface of semiconductors. The energy level system of qdots (or artificial atoms) is similar to the level system of atoms. Two different electron states of these dots can also represent qubits. More or less ordered structures can be formed. Structures with this type may become suitable to construct devices for quantum-informatics [6]. Entangled states of these dots or atoms are needed for this.

The existence of entangled states is one of the most curious properties of quantum mechanics. One of the first described consequences of this phenomenon is the EPR paradox [7] that points out the nonlocality of quantum systems.

The source of effectiveness of quantum encryption and quantum informatics is the existence of entangled states [8]. The method to produce entangled state is an important question. The environment usually induces decoherence so the entanglement of the system vanishes [8].

The quantitative classification of entanglement is still an open question. Wootters [9,10] found a quick method to calculate the entanglement of qubits of particle pairs. The method also works in the case of mixed states.

Investigating multipartite entanglement of particle systems is a more difficult task. The method of Meyer and Wallach [11] is able to determine the multipartite entanglement of the system of two level atoms in the case of pure states.

Multipartite entanglement of systems in mixed states can be described by witness operators. The exhaustive quantitative description and classification is not solved yet.

Our aim is to describe the time dependence of entanglement and decoherence of a chain of two-level atoms.

Methods of investigation

The propagation of light pulses in a material medium is a scattering phenomenon. The integral equation deduced from the Maxwell equations was discretized using the fourth order Simpson formula. The differential equations that describe the electric polarization were considered using a fourth order Hamming predictor-corrector method. The coupled integro-differential equations were solved numerically. Neither the rotating wave approximation nor the slowly varying envelope approximation were used.

The polariton resonance of semiconductor layer was described according to Ref. [12].

The semiconductor Bloch equations describing the resonance of the semiconductor in the optical domain was deduced using the method of Ref. [13] without using RWA. Examining the splitting in the spectrum of the third harmonic, a common fast Fourier transformation algorithm was used.

The quantum state of a dipole coupled chain of two level atoms was described using reduced density operators. The time evolution of the system was described by the superradiant master equation at zero temperature [14]. The differential equations were solved numerically using a fourth order Runge-Kutta method.

The entanglement of pair of atoms in the chain was calculated using the method of Wootters [9, 10]. To characterize the multipartite entanglement a witness operators was used. A sufficient condition can be formulated for the separability of a state using the sign of the expectation value in the particular state of the witness operator.

Results

1. The propagation of short light pulses is regarded as a scattering phenomenon and is described with integro-differential equations derived from the Maxwell equations. The integral equation formalism of the reflection, refraction and propagation is investigated without the slowly varying envelope approximation. The resonant and the nonresonant response of the layer are separated to take into account the background polarization. Later the method was modified according to the experimental situation of Ref. [5] and in order to describe the effect of the antireflection coating on the substrate.

2. The method described above was applied to the polariton model of GaAs semiconductor. The transient phenomena cannot be neglected when describing the reflection and transmission of pulses consisting of a few optical cycles at the 37.31 μm polariton resonance of a GaAs layer. The slowly varying envelope approximation is invalid in case of such short pulses. Comparing the results of the calculations made on the basis of our model and the model using the Fresnel formulae we found significant differences.

3. The differential equations describing the dynamics of the charges in the valence and conduction bands of semiconductors, the so called semiconductor Bloch equations, were discussed without the rotating wave approximation.

4. For excitation of the model semiconductor GaAs with few cycle long optical pulses we can observe higher spectral components in the third harmonic. The results of the calculations made on the basis of our theoretical model are in good accordance with the experiments of Ref. [5].

5. The dynamics of short linear chains of two-level atoms coupled by the electromagnetic field was investigated. The environment of photon modes leads to the disappearance of the initially present entanglement. The rate of this process depends on the separation of the atoms, and also on the initial state. With the aid of appropriate entanglement witnesses this rate was shown to be exceptionally low for the so-called subradiant states.

6. If the atomic separation is below the resonant wavelength, the effect of the environment is weaker than the dipole-dipole interaction and multipartite entanglement can be formed in the initial stage of time evolution.

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