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Physica E 29 (2005) 320–324
PHYSICA E
www.elsevier.com/locate/physe

Optimal quantum control of electron–phonon scatterings in artificial atoms

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Available online 24 June 2005

Abstract

We study the phonon-induced dephasing dynamics in optically excited semiconductor quantum dots within the frameworks of the independent Boson model and optimal control. It is shown that appropriate tailoring of laser pulses allows a complete control of the optical excitation despite the phonon dephasing, a finding in marked contrast to other environment couplings.

PACS: 73.21.La; 71.38.−k; 02.60.Pn; 42.50.Ct

Keywords: Quantum dots; Independent Boson model; Quantum control; Optimal control theory

1. Introduction

Quantum control in semiconductors has recently become a subject of enormous scientific and technological interest [1,2], motivated by the tremendous success of quantum optics in atomic and molecular systems [3], the emerging field of quantum information processing [4,5], and the high standards of semiconductor opto electronics. The primary goal in the application of quantum control is to fully exploit the quantum properties of quantum systems—e.g., atoms, molecules, or solids—, and to hereby bring the system into some highly non-classical state or to steer it through a sequence of desired states, the latter being a point of central importance for quantum computation applications. Quantum control is usually achieved by transferring the coherence from an external control, e.g., a laser pulse, to a *quantum coherence*, which allows for isolated systems to set deliberately the quantum mechanical state vector [6]. Isolated quantum systems are idealizations which cannot be realized since any system interacts with its environment. Through such environment couplings, the quantum system becomes entangled with the environment in an uncontrollable fashion,

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1386-9477/$ - see front matter
doi:10.1016/j.physe.2005.05.029

which leads to *decoherence*, a process within which the pureness of the quantum state and its controllability becomes degraded.

Within the field of *quantum control* one is seeking for control strategies that allow to steer the quantum state evolution despite the presence of decoherence. Efficient control strategies are known for simple systems, such as the celebrated stimulated Raman adiabatic passage control of a generic three-level system [7], which has found widespread applications in atomic systems. Although there are several proposals for related schemes in semiconductor nanostructures [8,9], it has become clear that, in many cases of interest, the description of a solid state system in terms of generic few-level systems is overly simplified and cannot account for the enhanced environment couplings in the solid state. A particularly interesting case is found in semiconductor quantum dots [10,11], often referred to as *artificial atoms*, where the optical excitation of an electron–hole pair in the state of lowest energy causes the deformation of the surrounding lattice but relaxation is completely inhibited because of the atomic-like carrier density of states. In coherent optical spectroscopy [1,2], which is sensitive to the optically induced coherence, this partial transfer of quantum coherence from the electron–hole state to the lattice degrees of freedom, i.e., phonons, results in *dephasing* [12–14]. It should, however, be noted that, contrary to other decoherence channels in solids where the system's wavefunction acquires an uncontrollable phase through environment coupling, in the independent Boson model the loss of phase coherence is due to the coupling of the electron–hole state to an ensemble of harmonic oscillators which all evolve with a coherent time evolution but different phase. This results in destructive interference and dephasing, and thus spoils the direct applicability of coherent carrier control. On the other hand, the coherent nature of the state-vector evolution suggests that more refined control strategies might allow to suppress dephasing losses. To address this problem, in this paper we examine phonon-assisted dephasing within the framework of *optimal control* [15–17] aiming at a most efficient control strategy to channel the system's wavefunction through a sequence of given states. We will find that appropriate tailoring of laser pulses allows to promote the system from the ground state through a sequence of excited states back to the ground state *without suffering significant dephasing losses*. Despite the widespread use of the independent Boson model, e.g., for the description of optical properties of localized states in solids or Mößbauer spectroscopy, to our best knowledge no such control strategy for suppression of environment losses has hitherto been reported in the literature.

2. Independent Boson model

In our theoretical approach we follow Refs. [13,14,18] and start with the usual independent Boson Hamiltonian. We describe the dot states in terms of a generic two-level system, with ground state 0 and excited state x, assuming a negligible contribution of excited exciton states due to the typically large energy splittings of several tens of meV [10] and of biexcitons, which, in optical experiments, can be achieved through appropriate polarization filtering. This two-level system is coupled to a reservoir of harmonic oscillators such that the interaction only occurs when the system is in the upper state [19]:

$$H = \sum_\lambda g_\lambda (a_\lambda + a_\lambda^\dagger)\,|x\rangle\langle x| + \sum_\lambda \omega_\lambda a_\lambda^\dagger a_\lambda - \frac{1}{2}(\Omega|x\rangle\langle 0| + \Omega^*|0\rangle\langle x|). \quad (1)$$

Here, the bosonic degrees of freedom λ with energy ω_λ are described by the field operators a_λ and $a_\lambda^\dagger$, and g_λ is the coupling constant between x and λ. We describe the light-matter coupling within the usual dipole and rotating-wave approximations [20] with Ω the Rabi frequency, and consider a spherical dot model and acoustic deformation potential interactions as the only coupling mechanism. For the description of the time evolution of the two-level system in the presence of the phonon coupling (1), we adopt a density-matrix approach with $\boldsymbol{u} = \langle \boldsymbol{\sigma} \rangle$ the Bloch vector, $s_\lambda = \langle a_\lambda \rangle$ the coherent phonon amplitude, and $\boldsymbol{u}_\lambda = \langle \boldsymbol{\sigma}(a_\lambda - s_\lambda) \rangle$ the phonon-assisted density matrix as dynamic variables [8,18,21]. The result-