Optical Response of Strongly-Driven Quantum Dots with Excitonic and Biexcitonic Transitions

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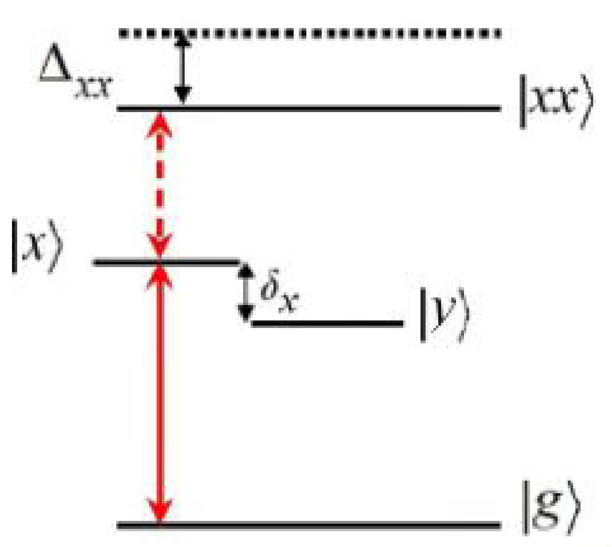
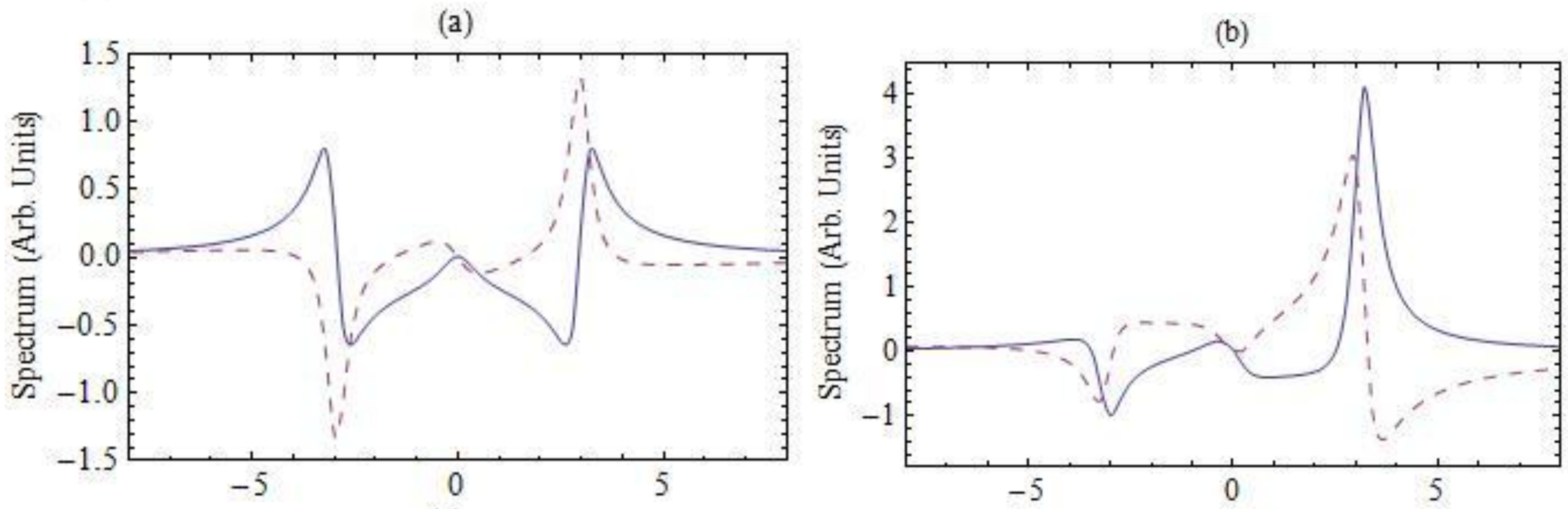
SCOPE OF THIS WORK: The nonlinear optical response of a two-level system interacting with a strong pump laser field and a weak probe laser field has been the subject of several studies for many years. The subject started 40 years ago with the seminal work of Mollow [1]. He showed that depending on the frequency and intensity of the pump field the probe field can be either absorbed, enhanced or remain intact [1]. In addition, ac-Stark shift effect is found to occur in this system [1]. In the area of semiconductor quantum dots, Xu et al. [2] investigated both theoretically and experimentally similar phenomena in a singly charged quantum dot under a strong optical driving field by probing the system with a weak optical field and found absorption, the ac-Stark effect, and optical gain. Also, Chang and Chuang [3] demonstrated that slow light can be created in the interaction of the single excitonic transition in a quantum dot with a weak probe and a strong pump field due to population oscillation.

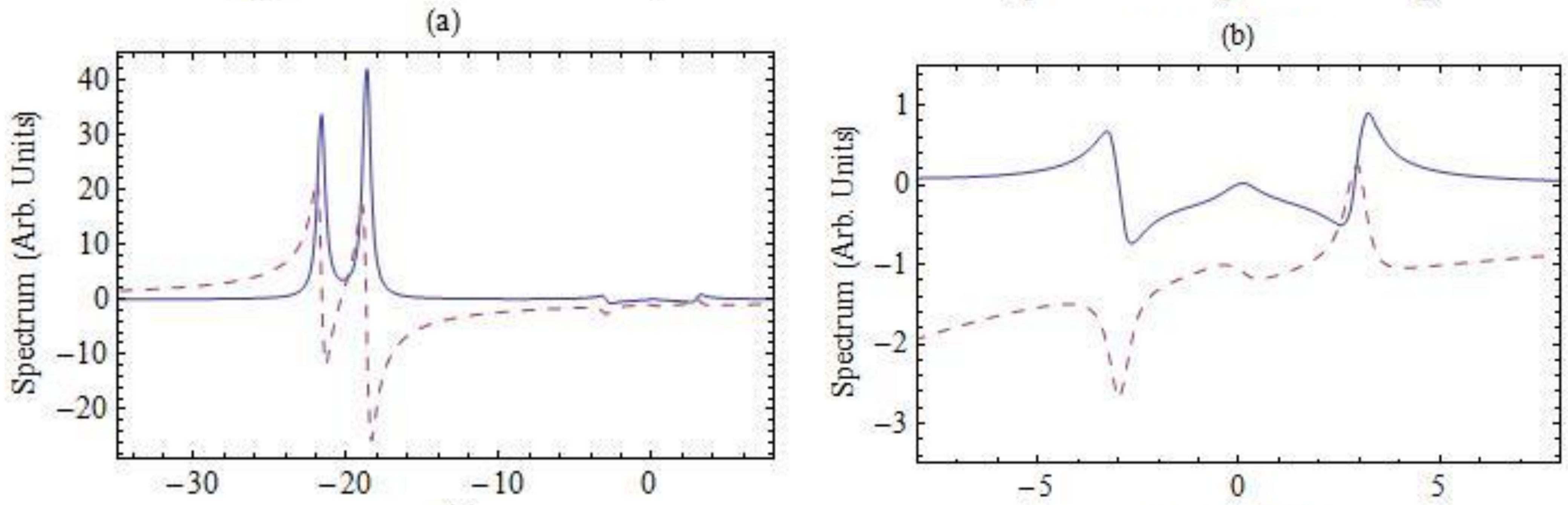
In the above two studies [2,3] the quantum dot structure is described with a two-level model. Here, we consider a semiconductor quantum dot system with both excitonic and biexcitonic transitions [4-6] that interacts with a weak probe laser field and a strong pump laser field. The system under study has two distinct optical transitions, one between the ground and the single-exciton state and one between the single-exciton and the biexciton state, making the system behaving as a ladder-type three-level system [7]. Furthermore, as the energy difference of the excitonic and biexcitonic transitions is small, the two transitions can be excited by a single laser field [4-6]. In this work, we extend the method presented in refs. [8,9] and obtain results for the optical properties of strongly-driven CdSe-based quantum dots. We show that the inclusion of the biexcitonic transition strongly modifies the optical absorption and dispersion of the probe laser field under the presence of the pump laser field. The optical absorption and dispersion spectra can be further modified by the frequency and intensity of the pump laser field.



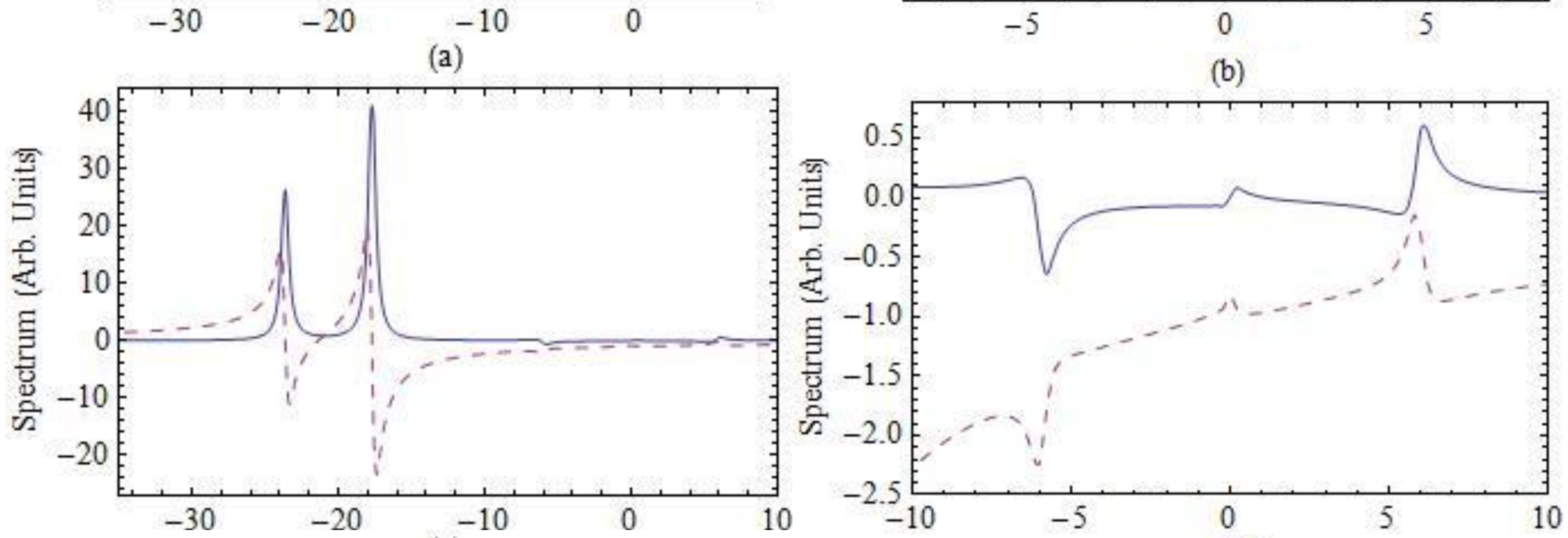
Left Figure:. Schematic of the level configuration of the quantum dot structure: a ladder-type system with excitonic and biexcitonic transitions. Here, δ_x is the fine-structure splitting and Δ_{xx} is the binding energy of the biexciton. We note that a quantum dot structure with excitonic and biexcitonic transitions is modeled in general as a four-level system [4]. The system is comprised of a ground state |g>, the single-exciton linearly polarized states |x> (x-polarized) and |y> (y-polarized) and the biexciton state |xx>. If one applies two linearly x-polarized electromagnetic fields that induce excitation in the transitions |g> →|x> →|xx>, while the state |y> remains uncoupled, then the quantum dot system has the structure of a three-level ladder-type system [4-7].



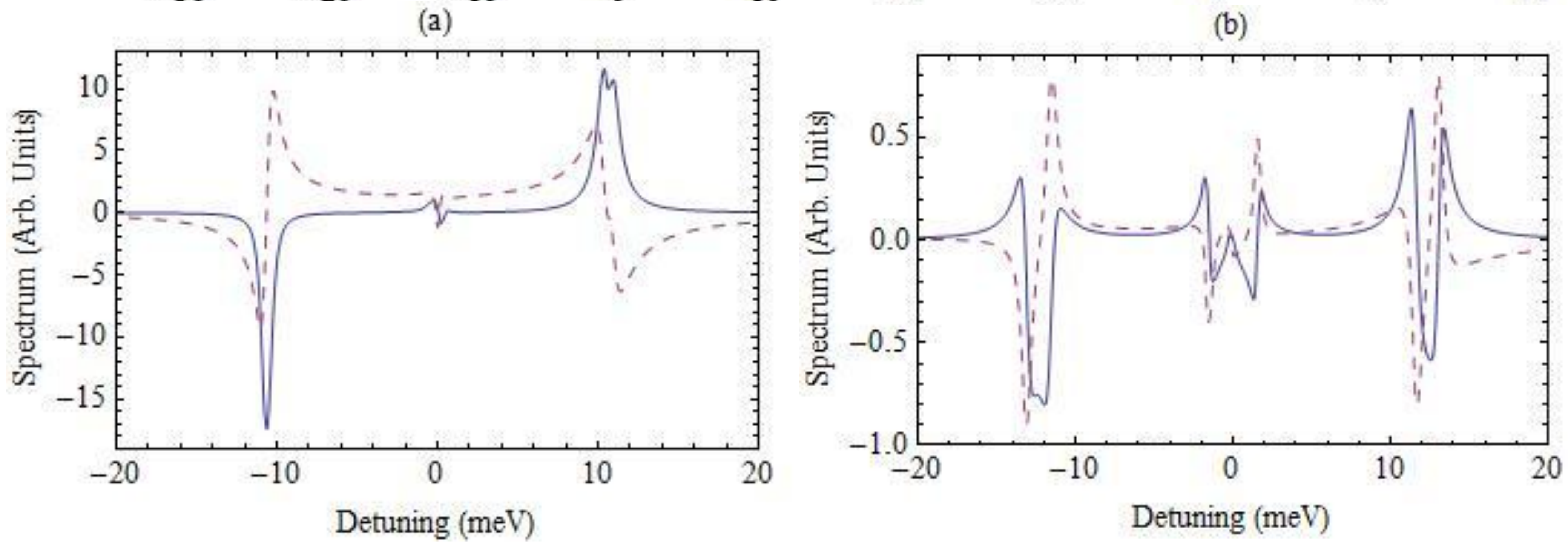
Left Figures: The case when the exciton-biexciton transition is omitted. (a) The absorption (solid curve) and the dispersion (dashed curve) spectrum, in arbitrary units, for the pump field at exact resonance with the |g> →|x> transition. The Rabi frequency of the pump field is $\hbar\Omega$ = 3 meV. We use parameters for CdSe–based quantum dots [6]. (b) The same as in (a) but with the pump field detuned from resonance by 1 meV. In (a) characteristic Mollow absorption-dispersion spectra are displayed that become asymmetric in (b) due to the detuning of the pump field.



Left Figures: The case when the exciton-biexciton transition is included. (a) The absorption (solid curve) and the dispersion (dashed curve) spectrum, in arbitrary units, for the pump field at exact resonance with the |g> →|x> transition. The Rabi frequency of the pump field is $\hbar\Omega$ = 3 meV (the same for both transitions). We use parameters for CdSe–based quantum dots [6]. (b) Inset of (a) around zero detuning of the probe field. A combination of Mollow absorption-dispersion spectra and Autler-Townes splitting spectra is found. The asymmetry of the two spectra can be explained, using an adiabatic elimination approach, due to the large binding energy of the biexciton.



Left Figures: The same as above but with four times the intensity of the pump field, leading to $\hbar\Omega$ = 6 meV.



Upper Figures: The same as above but with the pump field at two-photon resonance with the |g> →|xx> transition. (a) $\hbar\Omega$ = 3 meV, (b) $\hbar\Omega$ = 6 meV.

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