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Tunneling effect on second-harmonic generation in quantum dot molecule

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ABSTRACT

The tunneling effect on second-harmonic generation (SHG) coefficient in quantum dot molecule (QDM) is investigated theoretically. By using the compact-density matrix approach and the iterative method, we obtain an analytical expression of the SHG coefficient and numerical calculations for GaAs QDM. The results show that the tunneling strength, Rabi frequency and the size of the QDM have influences on the SHG coefficient.

1. Introduction

With the rapid development of epitaxy techniques in the past few years, it is possible to study the low-dimensional systems in nanoscale such as quantum well [1–7], quantum wire [8–13] and quantum dot. For a three dimensional confinement of carriers, quantum dot(QD) has been attracted the attention of many researchers. In 1999, quantum information processing by using quantum dot spins and cavity quantum electrodynamics was studied by A. Imamoglu et al. [14–17]. In addition, much attention have been paid to the nonlinear optical effects in QD, such as optical rectification (OR), second-harmonic generation (SHG), third-harmonic generation (THG), electro-optic effect (EOE), etc [18–22]. Because of such a low-dimensional system, QD may exhibit pronounced optical nonlinearity which could lead to finding out optical media with sufficiently large and quick nonlinear responses for various application.

With the femtosecond laser was invented, the Nonlinear Optics has developed rapidly in the recent years. As we all know, the SHG is one of the main nonlinear optical effects. With the powerful laser, the nonlinear material will radiate second harmonic light whose frequency is twice larger than the incident light. However, the SHG can not be observed in a symmetric quantum system. It is because that the optical transitions between the electronic states with the same parity are not allowed. For this reason, the signal of SHG has high sensitivity in detecting the structure symmetry change. With a such prominent feature, SHG has been studied in many fields by many researchers. In 2007, the SHG in parabolic quantum dots with electric and magnetic fields has been studied by Li *et al.* [23]. The result shows that the magnitude of electric and magnetic fields have a great influence on the SHG coefficient and the theoretical value of the SHG can be enhanced over $10^{-6}\ m/V$ by the applied fields. In 2013, Liu *et al.* studied the polaron effects on SHG in cylindrical quantum dots with magnetic field and obtained the two photon resonant peak of SHG with the electron-LO phonon interaction(ELOPI) is about over 15~22.5 times larger than that without the ELOPI [24]. Latter, in 2014, R.Khordad and H.Bahramiyan researched the SHG of modified Gaussian quantum

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dots under the influence of electron-LO phonon, electron-SO phonon, and electron-LO + SO phonon interations [25], Mou *et al.* studied the SHG in asymmetrical semi-exponential [26] and Zhai studied the SHG in asymmetrical Gaussian quantum wells [27], respectively.

Recently, some researchers have taken a great interest in quantum dot molecule (QDM), which can be fabricated using self-assembled dot growth technology or molecule beam epitaxy combing with in situ atomic layer precise etching [28,29]. An asymmetric quantum dot molecule consists of two QDs with different band structures which are coupled by tunneling. An electron can be excited from the valence band to the conduction band in a dot by a near resonance incident light, and the electron can tunnel to the other dot with the help of the external bias voltage. Since the tunneling effect is sensitive to external bias voltage, the interdot oscillations can be controlled by the applied voltage. Many works have been carried out many problems about the asymmetric QDM system, such as voltage-controlled slow light, tunneling induced transparency, exciton qubits, robust states, coherent control of tunneling [30–34].

In this paper, we study the nonlinear second-harmonic generation in an asymmetric QDM with tunneling effect. This paper is organized as follows. In Sec. 2, physical system and model, Hamiltonian, relevant eigen states and eigen energies will be discussed in detail. The analytical expressions for the nonlinear SHG are obtained by the compact-density matrix approach and the iterative method. Sec. 3 is devoted to the numerical results and discussions. Finally, a brief conclusion will be made in the Sec. 4.

2. Theory

Let us consider a QDM with two QDs. A schematic representation of the Hamiltonian for our model can be seen in Fig. 1 [30]. In Fig. 1(a), the interdot tunneling is weak because the levels are out of resonance without a gate voltage. On the contrary, Fig. 1(b) shows that with a gate voltage, the conduction-band levels in different QDs get close to resonance, the tunneling become much stronger than before while the valence-band levels are much more out of resonance. For this reason, we can neglect the hole tunneling and the Hamiltonian of the system can be represented in Fig. 1(c). $|0\rangle$ is the ground state without excitation. $|1\rangle$ is the direct-exciton state in one dot where an electron is excited from valence band to its conduct band with an incident pulse. By tunneling effect, an electron tunnel from one dot to another. We use $|2\rangle$ to describe such phenomenon called indirect exciton state which contains a hole in the first dot and an electron in the second dot. Using this configuration, the Hamiltonian can be written as [30].

$$\widehat{H} = \sum_j \hbar\omega_j |j\rangle\langle j| + T_e(|1\rangle\langle 2| + |2\rangle\langle 1|) + \hbar\Omega\left(e^{i\omega_L t}|0\rangle\langle 1| + e^{-i\omega_L t}|1\rangle\langle 0|\right), \tag{1}$$

where $\hbar\omega_j$ stand for the energy of the state $|j\rangle, j = 0,1,2$. T_e stand for the electron-tunneling strength. $\Omega = \frac{\mu_{01}E}{2\hbar}$ is one-half Rabi frequency for the probe laser field, here μ_{01} is the dipole momentum matrix element and E is the electric field amplitude, respectively. Applying the unitary transformation

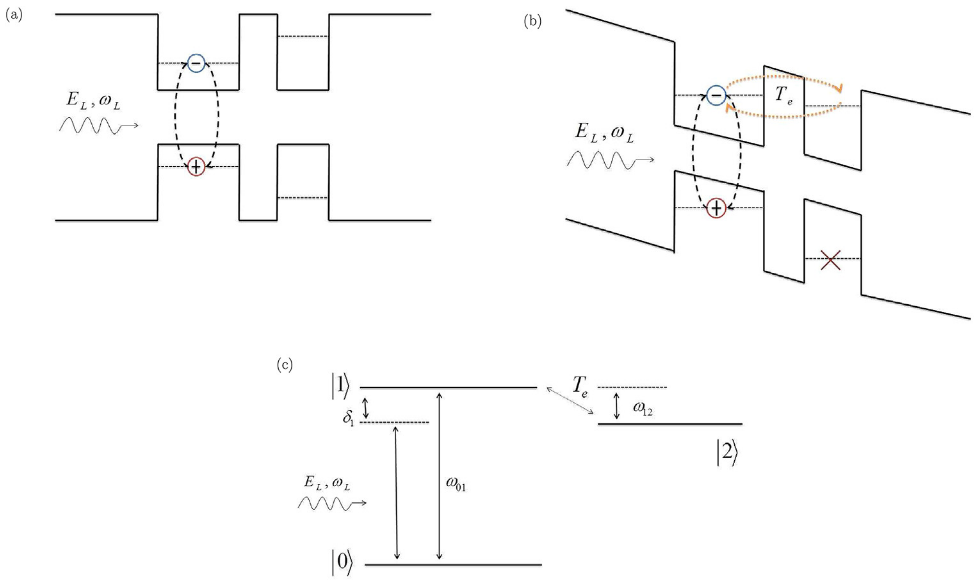

Fig. 1. Schematic band structure and level configuration of QDM. (a)Without a gate voltage, the tunneling is weak. (b)With applied a gate voltage, the conduction-band levels are resonance. The tunneling become stronger. (c)Scheme of energy levels on Hamiltonian.