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Influence of position-dependent effective mass on the nonlinear optical properties of impurity doped quantum dots in presence of Gaussian white noise

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ABSTRACT

We examine the influence of position-dependent effective mass (PDEM) on a few nonlinear optical (NLO) properties of impurity doped quantum dots (QDs) in presence and absence of noise. The said properties include total optical absorption coefficient (TOAC), nonlinear optical rectification (NOR), second harmonic generation (SHG) and third harmonic generation (THG). The impurity potential is modeled by a Gaussian function and the noise applied being Gaussian white noise. The profiles of above NLO properties have been pursued as a function of incident photon energy for different values of PDEM. Using PDEM the said profiles exhibit considerable departure from that of fixed effective mass (FEM). Presence of noise almost invariably amplifies the NLO properties with a few exceptions. A change in the mode of application of noise also sometimes affects the above profiles. The investigation furnishes us with a detailed picture of the subtle interplay between noise and PDEM through which the said NLO properties of doped QD systems can be tailored.

1. Introduction

Low-dimensional semiconductor systems (LDSS) such as quantum wells (QWLs), quantum wires (QWRs) and quantum dots (QDs) are well known for their noticeably large nonlinear optical (NLO) properties. A substantially large quantum confinement effect prevailing in LDSS becomes responsible for such enhanced nonlinear effects and the confinement becomes much stronger in comparison with the bulk materials. Such strong confinement in LDSS lowers the energy separation between the subband levels and amplifies the electric dipole matrix elements. The lowering and the amplification together favor accomplishment of resonance conditions. The enhanced NLO properties of LDSS give rise to rigorous investigations in view of varieties of applications e.g. probing the electronic structure of mesoscopic media, usage of electronic and optoelectronic devices in the infra-red region of the electromagnetic spectrum [1–4], deciphering the area of integrated optics and optical communications [5,6], and most significantly, realization of fundamental physics.

An overwhelmingly large fraction of research on various NLO properties of LDSS involve the *second-order nonlinear processes*, e.g. *nonlinear optical rectification* (*NOR*) and *second harmonic generation* (*SHG*). These two are the simplest and lowest-order nonlinear processes having magnitudes larger than those of higher-order ones, particularly, if the quantum system comprises of noticeable asymmetry [7]. These NLO response properties of LDSS can be correlated with the asymmetry of the confinement potential. The even-order susceptibilities disappear in a symmetric confinement potential and thus finite second-order susceptibilities can only be expected if the symmetry of the confining potential is destroyed [8,9]. Thus, in order to achieve desired finite second-order susceptibilities, tunable asymmetry of the confinement potential is of utmost importance [2]. The asymmetry can be realized either by applying an external electric field to the system or by exploiting sophisticated material growing technologies, such as molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD).

One of the second-order nonlinear processes, i.e. NOR has been subjected to considerable research recently that include the works of Duque and his collaborators [2,3,5,6], Hassanabadi et al. [4], Karabulut et al. [8], Yıldırım and Tomak [9], Karabulut and Şafak [10], Guo and his co-workers [11–13], Baskoutas et al. [7,14,15], Rezaei and his associates [16,17], and Xie and his group [18–22], to mention a few.

SHG is another important second-order NLO property which is extremely delicate to the symmetry of the systems. It is regularly used to study the second-order properties of surface and interfaces (such as QWLs) as a non-destructive and non-contact probe.

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We, therefore, find a substantial number of important investigations on SHG coefficient of LDSS by Duque and his collaborators [2,3,23], Hassanabadi et al. [4], Zhang and Xie [24], Liu et al. [25], Karabulut et al. [26], Sauvage et al. [27], Sedrakian et al. [28] and Guo and his group [1,29].

The *third-order* NLO properties assume importance in quantum systems having inversion symmetry. In this case, while the second-order susceptibility vanishes because of the inversion symmetry, the third-order one survives prominently and shows huge enhancement compared with the bulk material [30]. The augmented magnitude of the third-order nonlinearities in LDSS compared with the bulk materials stems from the quantum confinement effects favoring large oscillator strength of the intersubband transitions and from the band structure engineering, often conforming to the triple resonance requirements [31,32]. NLO substances with large third-order nonlinear susceptibilities χ^3 have emerged as inalienable components for the manufacturing of all-optical switching, modulating and computing devices [33]. Pioneering work on *third harmonic generation* (*THG*) susceptibilities of InAs/GaAs self-assembled quantum dots was first done by Sauvage et al. [34]. Later on, important works on THG susceptibility have been conducted by Şakiroğlu et al. [2], Zhang and Xie [30], Wang [31], Shao et al. [32], Liu et al. [33], Yıldırım and Tomak [35], Vaseghi et al. [36], Shao et al. [37], Zhai et al. [38], Wang et al. [39], Niculescu et al. [40], Kirak and Altinok [41], Radovanović et al. [42], and Cristea et al. [43], to mention a few.

Introduction of impurity (dopant) into LDSS triggers rich interplay between the dopant potential with the confinement potential of LDSS which effectively alters the energy level distribution. Consequently, the electronic and optical properties of LDSS also undergo huge change. Thus, a regulated inclusion of dopant helps achieving desirable optical transitions. Such desirable optical transition plays anchoring role in manufacturing optoelectronic devices with tunable emission or transmission properties and ultranarrow spectral linewidths. This has largely enlarged the domain of technological applications of LDSS. Moreover, the interplay between the optical transition energy and the confinement strength (or the quantum size) can effectively fine-tune the resonance frequency. In what follows, optical properties of doped LDSS have envisaged tremendous research activities [18,44–65].

Recently, we come across a considerable number of investigations which include *position-dependent effective mass* (*PDEM*) of LDSS. PDEM leads to significant change in the binding energy of the doped system and thus modifies the optical properties. Such change in the optical properties has induced intense research activities on LDSS with spatially varying effective mass in recent years. In this context the works of Rajashabala and Navaneethakrishnan [66–68], Peter and Navaneethakrishnan [69], Khordad [70,71], Qi et al. [72], Peter [73], Li et al. [74], and Naimi et al. [75] deserve mention.

Of late, we have performed detailed studies on the role of *noise* in tailoring some *second and third-order nonlinear optical properties* of QD devices [76–78]. In the present study we explore the influence of *position-dependent effective mass* (*PDEM*) on the *total optical absorption coefficient* (*TOAC*), *nonlinear optical rectification* (*NOR*), *second harmonic generation* (*SHG*) coefficients, and *third harmonic generation* (*THG*) coefficients of doped QD in presence of *Gaussian white noise*. The system under study being a 2-d QD (GaAs) consisting of single carrier electron under parabolic confinement in the x–y plane. The QD is doped with an impurity represented by a Gaussian potential in the presence of a perpendicular magnetic field which acts as an additional confinement. An external static electric field has been applied to the system. Gaussian white noise has been administered to the doped QD via two different pathways, i.e. additive and multiplicative [76–78]. The profiles of above optical properties are pursued as a function of frequency of incident radiation, simultaneously with *fixed effective mass* (*FEM*) and *dopant position-dependent effective mass (PDEM)* which reveals some interesting results.

2. Method

The impurity doped QD Hamiltonian, subject to external static electric field (F) applied along x and y-directions and spatially δ-correlated Gaussian white noise (additive/multiplicative) can be written as

$$H_0 = H_0' + V_{imp} + |e|F(x + y) + V_{noise}. \tag{1}$$

Under effective mass approximation, H_0' represents the impurity-free 2-d quantum dot containing single carrier electron under lateral parabolic confinement in the x–y plane and in presence of a perpendicular magnetic field. $V(x, y) = \frac{1}{2}m^*\omega_0^2(x^2 + y^2)$ is the confinement potential with ω_0 as the harmonic confinement frequency. H_0' is therefore given by

$$H_0' = \frac{1}{2m^*}\left[-i\hbar\nabla + \frac{e}{c}A\right]^2 + \frac{1}{2}m^*\omega_0^2(x^2 + y^2). \tag{2}$$

m^* represents the effective mass of the electron inside the QD material. Using Landau gauge [$A = (By, 0, 0)$,], where A is the vector potential and B is the magnetic field strength] H_0' reads

$$H_0' = -\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) + \frac{1}{2}m^*\omega_0^2x^2 + \frac{1}{2}m^*(\omega_0^2 + \omega_c^2)y^2 - i\hbar\omega_c y\frac{\partial}{\partial x}, \tag{3}$$

$\omega_c = \frac{eB}{m^*}$ being the cyclotron frequency. $\Omega^2 = \omega_0^2 + \omega_c^2$ can be viewed as the effective confinement frequency in the y-direction. The dopant location-dependent effective mass $m^*(r_0)$ where $r_0 = \sqrt{x_0^2 + y_0^2}$ is given by [66,69]

$$\frac{1}{m^*(r_0)} = \frac{1}{m^*} + \left(1 - \frac{1}{m^*}\right)\exp(-\beta r_0), \tag{4}$$

where β is a constant chosen to be 0.01 a.u. The choice of above form of PDEM indicates that the dopant is strongly bound to the dot confinement center as $r_0 \to 0$, i.e. for on-center dopants whereas $m^*(r_0)$ becomes highly significant as $r_0 \to \infty$, i.e. for far off-center dopants.

V_{imp} is the impurity (dopant) potential represented by a Gaussian function [76–78] viz. $V_{imp} = V_0\, e^{-\gamma\left[(x-x_0)^2+(y-y_0)^2\right]}$. (x_0, y_0) is the site of dopant incorporation, V_0 is the strength of the dopant potential, and γ^{-1} represents the spatial spread of impurity potential. γ can be written as $\gamma = k\varepsilon$ where ε is the static dielectric constant of the medium and k is a constant.

The term V_{noise} represents the noise contribution to the Hamiltonian H_0. It consists of a spatially δ-correlated Gaussian white noise $[f(x, y)]$ which assumes a Gaussian distribution (generated by Box–Muller algorithm) having strength ζ and is described by the set of conditions [76–78]:

$$\langle f(x, y)\rangle = 0, \tag{5}$$

the zero average condition, and

$$\langle f(x, y)f(x', y')\rangle = 2\zeta\delta\big((x, y) - (x', y')\big), \tag{6}$$

the spatial δ-correlation condition. The Gaussian white noise can be applied to the system via two different modes (pathways), i.e. additive and multiplicative [76–78]. In case of additive white noise V_{noise} becomes

$$V_{noise} = \lambda_1 f(x, y). \tag{7}$$

And with multiplicative noise we can write