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Modulating nonlinear optical properties of impurity doped quantum dots via the interplay between anisotropy and Gaussian white noise

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ABSTRACT

The influence of anisotropy on various nonlinear optical (NLO) properties such as total optical absorption coefficient (TOAC), nonlinear optical rectification (NOR), second harmonic generation (SHG) and third harmonic generation (THG) of impurity doped quantum dots (QDs) have been investigated in presence and absence of noise. Noise has been applied to the system additively and multiplicatively. The impurity potential is modeled by a Gaussian function and the noise applied being Gaussian white noise. A perpendicular magnetic field emerges out as a confinement source and a static external electric field has been applied. Profiles of the optical properties have been monitored as a function of incident photon energy for different values of anisotropy. In this connection the role of mode of application of noise (additive/multiplicative) has also been analysed. The interplay between noise and anisotropy has been found to profoundly affect the NLO properties. The investigation reveals that there are only one or two anisotropy regimes (depending on the particular NLO property under consideration) where noise-induced enhancement of the NLO property can be realized. Thus, anisotropy appears to be the central parameter by which the noise-induced enhancement of 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) have garnered wide recognition for their noticeably large nonlinear optical (NLO) properties. Extremely large quantum confinement effect prevailing in LDSS becomes responsible for such enhanced nonlinear effects and the said confinement happens to be much stronger in comparison with the bulk materials. Such strong confinement in LDSS leads to small energy separation between the subband levels and large value of electric dipole matrix elements. These two factors work in unison for smooth achievement of resonance conditions. Landmark work on NLO properties of QWLs was first carried out by Ahn and Chuang [1]. Later on, the enhanced NLO properties of LDSS have catalyzed an abundance of investigations related with probing the electronic structure of mesoscopic media, application of electronic and optoelectronic devices in the

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infra-red region of the electromagnetic spectrum [2–5], exploring the area of integrated optics and optical communications [6,7], and most significantly, understanding and appreciation of fundamental physics.

Among the various NLO properties much attention has been paid to 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 usually greater than those of higher-order ones, particularly, if the quantum system possesses noticeable asymmetry [8]. These NLO response properties of LDSS are closely linked with the asymmetry of the confinement potential. The even-order susceptibilities get eliminated in a symmetric quantum well structure and thus finite second-order susceptibilities can only be observed if the symmetry of the confining potential is broken [9,10]. Thus, in order to achieve desired finite second-order susceptibilities, tunable asymmetry of the confinement potential is of prime importance [3]. The asymmetry is generated either by applying an external electric field to the system or by using 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 paid considerable attention recently and we observe several notable works related to this by Duque and his collaborators [3,4,6,7], Hassanabadi et al. [5], Karabulut et al. [9], Yıldırım and Tomak [10], Karabulut and Şafak [11], Guo and his co-workers [12–14], Baskoutas et al. [8,15,16], Rezaei and his associates [17,18], and Xie and his group [19–23], to mention a few.

SHG is another important second-order NLO property which is extremely sensitive to the symmetry of the systems. It is routinely used to study the second-order properties of surface and interfaces (such as QWLs) as a non-destructive and non-contact probe. We, therefore, find a substantial number of important investigations on SHG coefficient of LDSS by Duque and his collaborators [3,4,24], Hassanabadi et al. [5], Zhang and Xie [25], Liu et al. [26], Karabulut et al. [27], Sauvage et al. [28], Sedrakian et al. [29] and Guo and his group [2,30].

The *third-order* NLO properties, too, deserve special attention in several quantum systems having inversion symmetry. In this case, while the second-order susceptibility disappears because of the inversion symmetry, the third-order one divulges huge enhancement compared with the bulk material. Therefore, for LDSS without inversion symmetry, generally only the second-order NLO properties draw maximum attention, while the third-order NLO properties lack attention that they deserve [31]. The amplified magnitude of the third-order nonlinearities in LDSS compared with the bulk materials arises out of the quantum confinement effects leading to large oscillator strength of the intersubband transitions and from the band structure engineering, often supporting the triple resonance requirements [32,33]. NLO materials with large third-order nonlinear susceptibilities χ^3 have emerged as inalienable components for the manufacturing of all-optical switching, modulating and computing devices [34]. Pioneering work on *third harmonic generation (THG)* susceptibilities of $InAs/GaAs$ self-assembled quantum dots was first done by Sauvage et al. [35]. Later on, important works on THG susceptibility have been carried out by Şakiroğlu et al. [3], Zhang and Xie [31], Wang [32], Shao et al. [33], Liu et al. [34], Yıldırım and Tomak [36], Vaseghi et al. [37], Shao et al. [38], Zhai et al. [39], Wang et al. [40], Niculescu et al. [41], Kirak and Altinok [42], and Cristea et al. [43], to mention a few. At this point of discussion it needs to be mentioned that the problem of higher harmonic generation in AC electric field driven by the gate electrodes and not light field is now observed in carbon nanotubes [44].

Introduction of impurity (dopant) into LDSS initiates profound interplay between the dopant potential with the confinement potential of LDSS which eventually alters the energy level distribution. Such alteration, in turn, severely changes the electronic and optical properties of LDSS. Thus, a regulated ingression of dopant could be judicious in achieving desirable optical transitions. Such desirable optical transition has become part and parcel of manufacturing optoelectronic devices with tunable emission or transmission properties and ultranarrow spectral linewidths. This has largely widened the domain of technological applications of LDSS. Moreover, the intimacy between the optical transition energy and the confinement strength (or the quantum size) can gracefully fine-tune the resonance frequency. In what follows, optical properties of doped LDSS have been exposed to rigorous research activities [45–60].

Recently, we envisage a few important investigations which deal with influence of *geometrical anisotropy* on the optical properties of LDSS. Among them the works of Xie and his coworkers [61–63] and Safarpour et. al. [64,65] merit mention. Indeed, in most cases LDSS are not at all isotropic which justifies the need of understanding how anisotropy affects their optical properties. In practice anisotropic QDs can be realized by chemically controlling the nanostructure aspect ratio [62]. Thus, study of anisotropic systems has generated considerable interest in view of obtaining novel as well as useful dividends.

Of late, we have performed detailed studies on the role of *noise* in controlling a few optical properties of QD devices [66,67]. In the present study we explore the influence of *geometrical anisotropy* 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 [66,67]. The profiles of above optical properties are pursued as a function of frequency of incident radiation for different extents of geometrical anisotropy 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