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Fano resonance and resonant localization of excitonic wave in one-dimensional quantum dot array with a ring

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ABSTRACT

The Fano interference of excitonic wave transmitting through a quantum dot chain array with a ring and the Anderson-like localization of the excitonic wave in the ring side are studied. In the quantum dot chain array with a ring, propagating excitonic waves via resonant dipole–dipole interaction interfere with the scattered excitonic wave from the ring and results in the Fano resonance. The excitation energy through the ring is transmitted, reflected, or localized depending on the dipole–dipole couplings to the Fano defect in the ring and transition energy detuning of the defect. Consequently, under some particular conditions, the excitation is resonantly localized in the ring side in the sense of Anderson-like localization by the destructive interference of the totally reflected wave from the ring with the incoming excitonic wave.

1. Introduction

Quantum dot (QD) chain arrays on a planar semiconductor substrate of photonic band gap structures are promising materials for a number of technological applications such as near-field waveguiding below the diffraction limit and optical switching applications [1,2]. The arrays of QDs are able to support electromagnetic excitation energy transport via Förster-type coupling. Their extended excitation over the whole array system leads to the formation of delocalized Frenkel-type exciton states when QDs are sufficiently closely-spaced and nearly identical for coherent coupling among QDs [3,4]. In such nanoarray with side-coupled system which modifies near-field waveguiding, the efficiency of the waveguiding is based on fundamental physical phenomena, i.e., transport of excitations and their resonances associated with the Fano resonance. The phenomenon of Fano resonance is ubiquitous in a variety of wave scattering by nanostructures [5]. This resonance results from the interference between a backbone system supporting a continuum of states and a side-coupled system with discrete levels [6–8]. Depending on the structure of the side-coupled system, the scattering of excitonic waves involves propagation along different paths and, as a consequence, results in Fano interference phenomena, which may be manipulated synthetically. Resultantly, constructive interference leads to resonant enhancement and destructive interference causes resonant suppression of the transmission [4,9].

Recently, a variety of experimental and theoretical work has performed to observe the Fano interference in different nanostructures in various fields [10–14]. As a typical example for the study of the Fano resonances, the transmission properties of electromagnetic waves through the waveguides created by an array of defect embedded into an otherwise perfect two-dimensional photonic crystal has been studied [5,15,16]. In such structures composed of discrete waveguide system in two-dimensional photonic-crystal, the electromagnetic wave scatters and shows peculiar transmission properties of resonant transmission or reflection due to the interference of a linear chain of particles with side-coupled defects. One of the main features of the Fano resonance is its asymmetric line profile. The asymmetry originating from the interaction of a discrete localized state with a continuum of propagation modes is shown for electromagnetic energy transport through the system of the continuum [17]. It has also been reported that the Fano interference is able to trigger the so-called Anderson localization, which is arising from the destructive interference of waves propagating in static disordered media [18,19]. In practice, for a system composed of the continuum and the discrete system (Fano defect), the Fano interference supplies the ability of the excitation localization to the Fano defect via a weak coupling of the

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regular backbone system to the defect [5,9].

In this paper, we study the Fano interference of excitonic wave transmitting through a quantum dot chain array with a ring and the localization of the excitonic wave to the Fano defect in the ring side. In practice, the properties of the transmission of the excitonic wave through the similar system via Coulomb dipole–dipole interaction has been analyzed in our previous study [9]. It was for the characterization of the propagation of exciton-wave through a Mach-Zehnder interferometer type nanocrystal chain array and its results showed that the quantum interference in the excitation transport comes from supplying different paths of the transported excitation energy [6,9,20]. As an extension of the previous study, we are interested in the characteristic feature of the transmission, reflection, and especially localization of the excitonic wave in a linear chain with a ring [21]. The purpose of this study is to relate resonant scattering to Fano interferences and excitation localization [22]. The localization of the electromagnetic excitation energy in our one-dimensional system with a ring can be a model of the Anderson-like localization. We investigate the interplay between the Fano interference and the Anderson-like localization mechanism. The next section describes the model and the local density of states (LDOSs) with respect to the quantum dots (QDs) belonging to the ring. Results and discussion are given in Section 3. In the Section we discuss the resonance and antiresonance of the LDOSs and study how their position and lineshape depend on the parameters of the coupled QD in the ring. Finally, we summarize our results and conclude briefly in Section 4.

2. Model and theory

An excited QD in a linear array interacts with other QDs by the instantaneous direct longitudinal Coulomb coupling, i.e., resonant dipole–dipole interaction (RDDI) between the virtual electromagnetic field generated by the resonant transition dipole of an excited donor QD and the polarization of a ground-state acceptor QD when the distance between the dipoles is much less than the transition wavelength. Hence its excitation transfer rate is proportional to the overlap between the emission spectrum of the donor QD and the absorption spectrum of the acceptor QD [23,24]. This non-radiative excitation transport is different from electronic transport in that there is no net transport of charge. Here we consider the case that the transport of charge is inhibited due to the passivation of the surface of QDs [25,26]. The dipole–dipole coupling energy J_{ij} between i-th and j-th QDs with orientational factor is $J_{ij} = [\vec{\mu}_i \cdot \vec{\mu}_j - 3(\vec{\mu}_i \cdot \hat{n})(\vec{\mu}_j \cdot \hat{n})]/4\pi\varepsilon R^3$, where $\vec{\mu}$ is the transition dipole moment of a QD, ε is the dielectric constant of the surrounding medium, and R is the inter-QD separation, $\hat{n}$ is the normalized inter-QD vector. In this paper we consider a closely spaced quantum dot chain array with a quantum dot ring in a photonic band gap structure and its schematic diagram is shown in Fig. 1(a). We particularize our study to the simple case with only one quantum dot is coupled as a Fano defect. As a reference, the so-called Fano defect is a discrete system embedded into an otherwise perfect one-dimensional array. Besides this, we consider two couplings of the defect with two nearest neighbors in the backbone as depicted in Fig. 1. The excitation energy through the ring is transmitted, reflected, or localized depending on the dipole–dipole couplings to the Fano defect in the ring and transition energy detuning of the defect as depicted in the conceptual illustrations of Fig. 2. In order to describe exciton transport in quasi-one dimension, a tight binding model with only nearest neighbor interaction can be employed [7,8]. The Hamiltonian in the presence of an impurity at site 'd' then takes the form of the Fano-Anderson model [7].

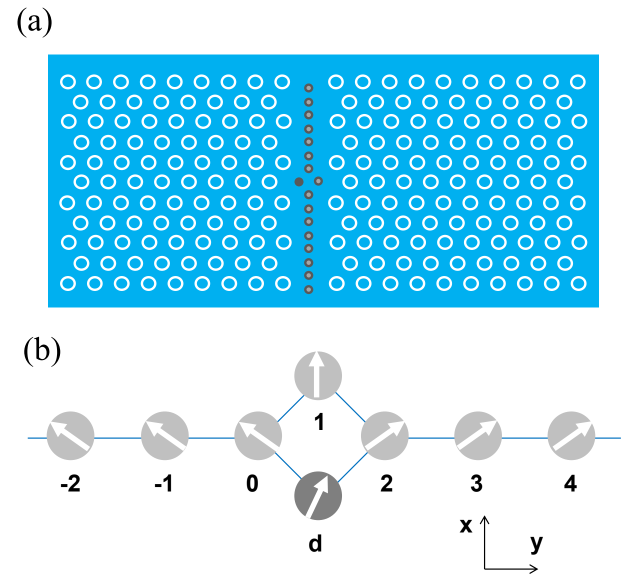

Fig. 1. (a) Schematic diagram of the quantum dot chain array with a ring in a photonic band gap material. (b) Quantum dot chain array with a ring with site numbers and possible dipolar orientations.

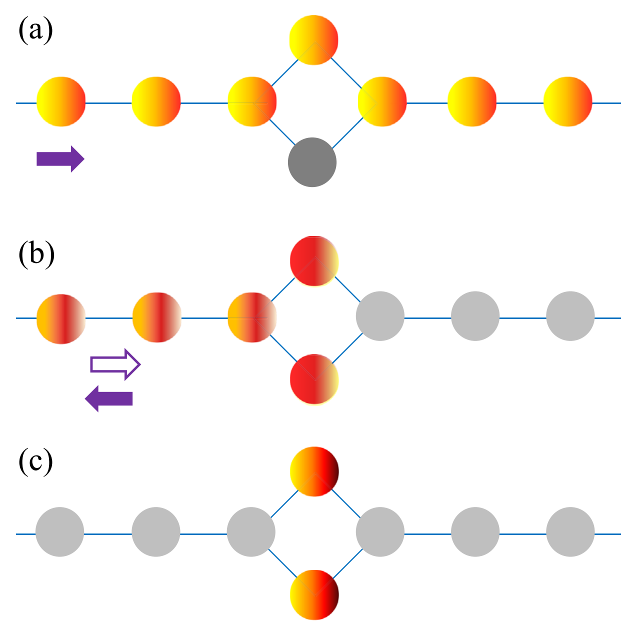

Fig. 2. Conceptual diagram of the (a) transmission, (b) reflection, and (c) localization of an excitonic wave incident from far left of the QD chain.

$$\hat{H} = \frac{\omega_0}{2}\sum_i \sigma_i^z + \frac{\omega_d}{2}\sigma_d^z + J\sum_i\left(\sigma_i^\dagger\sigma_{i+1} + \sigma_i\sigma_{i+1}^\dagger\right) + V\left(\sigma_d^\dagger\sigma_0 + \sigma_0\sigma_d^\dagger\right) + W\left(\sigma_d^\dagger\sigma_2 + \sigma_2\sigma_d^\dagger\right), \quad (1)$$

where and ω_d are transition energies of the QD of the backbone part and the QD of the site at 'd' of the ring part, respectively. J and V, W are the Coulomb couplings between QDs of the backbone part, and the couplings between the two QDs of the backbone and the QD at the lower part of the ring, respectively, and we let $\hbar = 1$ for simplicity. The Pauli operators σ_i^z, $\sigma_i^\dagger$, and σ_i describe inversion, excitation and deexcitation of the i-th QD, respectively. In this study, we consider the transition wavelength of the QD's is assumed to be in a stop band of the surrounding photonic band gap