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Effect of disorder on the radiative coupling between distant quantum dots embedded in a photonic crystal dimer

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ABSTRACT

Quantifying the radiative coupling between distant quantum emitters can be relevant for applications in quantum information processing on chip. Here we focus on semiconductor quantum dots embedded in photonic crystal dimers formed by two nominally identical L3 cavities, and we show that the effective radiative coupling between them is relatively robust against non-perfect quantum dot positioning and also, to a smaller extent, to structural disorder in the photonic crystal. We show that the coupling between the quantum dots is enhanced at resonance with the dimer photonic modes and is proportional to the quality factors of these modes as long as the two cavities are strongly coupled. We find that, for the configuration where the L3 defects are aligned along the horizontal axis, the radiative coupling is almost two times larger than the values obtained in previous work.

1. Introduction

In the last two decades, semiconductor quantum dots (QDs) have attracted considerable attention since they are promising candidates to realize solid state quantum bits (qubits) to be employed in quantum information and communication technology; their characteristic discrete spectra, long coherence times, and large oscillator strengths make them almost ideal *artificial atoms* that can be fixed in position and integrated into semiconductor structures [1]. The realization of two coherently interacting QDs and the possibility to externally control such interaction are crucial requirements to perform two-qubit operations, which are the building blocks of a quantum information protocol [2]. Nevertheless, the interaction strength between two QDs decays rapidly as a function of the inter-dot distance [3], which makes entanglement challenging when their distances are larger than their characteristic emission wavelength. Hence, there is a growing theoretical [4–6] and experimental [7–9] interest to mediate the dot–dot coupling through electromagnetic modes in a semiconductor photonic crystal (PC) structure. Due to their exceptional capabilities to efficiently guide and confine the electromagnetic radiation [10], and the high degree of precision in fabrication techniques currently achieved [11–13], PC structures should allow to overcome the short-range Förster coupling between interacting QDs, thus achieving sizable effective radiative coupling at distances quite larger than their emission wavelength [14,15]. The key parameters leading to a sizable radiative coupling between QDs in resonance with a given photonic mode are either the coupling strengths between each QD and the mode, or the total

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(intrinsic and extrinsic) photonic mode and QD loss rates. The former quantity increases as the modal volume decreases, for two QDs that are spatially positioned at an electric field antinode of the corresponding photonic mode, and the latter has to be small compared to the QD-mode coupling strengths. Recently, we have shown that photonic crystal molecules (PCM), which are systems formed by two or more coupled PC cavities, naturally fulfill the required conditions [16]. In fact, the normal modes associated to PCM are strongly localized in the PC cavities, allowing modal volumes next to the diffraction limit, and quality factors can be even larger (i.e., smaller losses) than the quality factors of the decoupled cavities [17]. In addition, it has been shown recently that it is possible to have strongly coupled PC cavities at inter-cavity distances which are quite larger than the characteristic wavelength of the system in a PCM [18].

In our previous work, we addressed the possibility of using a photonic crystal dimer (PCD), which consists of two-site PCM with two identical PC cavities, to mediate the radiative coupling between two QDs coupled to the normal modes of the dimer [16]. We adopted a semiclassical formalism based on the Green's function method [15,14] where the classical electromagnetic field is solved using Maxwell's equations within a guided mode expansion (GME) approach [19], and the optical response of the QDs is introduced in the model through a quantum susceptibility tensor. Here our interest is twofold. In the first part of this paper, we review the approach introduced in our previous work, and apply it to a PCD composed of two PC cavities with optimized design for high quality factor and diffraction-limited mode volume. We present original results for the inter-dot coupling strength as a function of the inter-cavities distance, for the situations in which the two cavities are aligned along 0° and 90° of the main cavity axis, respectively. We find that for the 0° configuration the coupling strength is almost two times larger than the values reported in the previous work, and this strength remains of the same order of magnitude when the non-perfect positioning of the QDs within the cavities is considered. In the second part, we study the effect of the structural PC disorder on the effective coupling between the two QDs, which is attributed to small errors in the fabrication process (hole position, shape and size in a slab PC of circular holes). Since structural disorder in PCs can increase significantly the losses of the PC cavities [20,21], and localize the field intensities of the molecular photonic modes in only one of the cavities (bared cavity modes) [22], the net effect of disorder on the PC-QD system is to reduce the effective dot–dot interaction. We find that when the structural disorder (quantified by the magnitude of the random fluctuations σ_S with Gaussian probability) is of the order of the coupling constant between the cavities, the effective energy transfer between the QDs remains of the same order of magnitude, which verifies the robustness of our system against a structural PC disorder of this magnitude. Although this amount of disorder is around five times smaller than the present state of the art [23] it should be achieved in the near future as fabrication techniques improve.

2. Radiative coupling between the quantum dots

The PCD that we study in this work is formed by two L3 cavities in a PC slab of a hexagonal lattice of air holes in GaAs. In the PC community, the L3 cavity is commonly defined by three missing holes in a horizontal line of the photonic lattice [24]; we choose the optimized design where the radius of the two end lateral holes are diminished to 80% of their original value, and the centers are outward displaced by $0.15a$, where a is the lattice parameter [25]. We focus on the two dimers where the line connecting the centers of the cavities determines an angle of 0° or 90° with respect to the horizontal axis. Typical values for GaAs PC structures coupled to InAs QDs in the 900 nm wavelength range are considered [26]: lattice parameter $a = 260$ nm, hole radius of 65 nm, slab thickness of 120 nm and refractive index of 3.41. The photonic eigenmode dispersion of the PCD is solved using the GME method, in which the electromagnetic fields of the PC slab are expanded in a guided mode basis associated to the homogeneous slab, and the quality factors are calculated via time-dependent perturbation theory using the photonic golden rule. For details of this theoretical approach, we refer to Ref. [19]. Moreover, to study the PCD-QD system we adopt a semiclassical formalism in which the electromagnetic field is solved classically using Maxwell's equations, and the optical response of the QDs is considered in the polarization vector through a quantum susceptibility tensor in the linear regime. The inhomogeneous differential equation is solved using the Green's function method, where the Green's tensor is expanded in the orthonormal basis of the PC eigenstates computed with GME. Since we are interested in the two normal eigenstates arising from the split states of the fundamental L3 cavity mode, there are only two eigenmodes in the expansion, one of them even (bonding), subscript $+$, and the other odd (antibonding), subscript $-$, with respect to the symmetry point of the structure. The poles of the PCD-QD coupled system are interpreted as the polariton modes whose associated eigenvectors carry the information of the bare-exciton and bare-photon fractions of the mixed state [14]. Additionally, the effective radiative coupling between two QDs is quantified by the components of the Green's tensor evaluated at the position of the QDs. The dominant component of the Green's tensor in our case is the yy due to the dominant polarization of the normal modes in the y direction, and to the small value of the x electric field component at the center of the L3 cavities, which is identically zero for the fundamental isolated-L3 cavity mode. Therefore, considering the two dimer modes with y electric field components, $E_{1,y}$ and $E_{2,y}$, frequencies $\omega_1 = \min(\omega_+,\omega_-)$ and $\omega_2 = \max(\omega_+,\omega_-)$ with normal mode splitting $\Delta=\omega_2-\omega_1$, and associated loss rates $\gamma_1=\omega_1/Q_1$ and $\gamma_2=\omega_2/Q_2$, the effective radiative coupling between the two QDs positioned at the centers of the cavities, i.e., $\mathbf{r}_1$ and $\mathbf{r}_2$, at the excitonic transition frequency ω, can be reduced to the following formal expression [16]:

$$G^{12}_{yy}(\omega) = \frac{2\pi\omega d^2}{\hbar}\left(\frac{E_{1,y}(\mathbf{r}_1)E^*_{1,y}(\mathbf{r}_2)}{\omega_1 - i\frac{\gamma_1}{2} - \omega} + \frac{E_{2,y}(\mathbf{r}_1)E^*_{2,y}(\mathbf{r}_2)}{\omega_2 - i\frac{\gamma_2}{2} - \omega}\right), \tag{1}$$