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Excitation Transfer between Distant Quantum Dots in Photonic Crystal Waveguide

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ABSTRACT We have theoretically studied the excitation transfer between distant quantum dots in a photonic crystal waveguide. Due to Anderson localization of disordered position and size of the photonic crystal holes was found to have a highly nontrivial effect on the interaction. We have simulated realistic systems with different magnitudes of the disorder and showed that while localization indeed has a profound effect on both range and magnitude of the dot-dot excitation transfer rate at several μm distance. The average excitation transfer rate was found to be larger than $10\mu eV$ at distance on the order of $10\mu m$. The transfer time to this corresponded was on the order of 10 ps, close to the single qubit operation time and much shorter than the decoherence time measured. The obtained results were found in good agreement with previous results.

KEYWORDS Excitation transfer, Quantum Dot, Waveguide, Photonic Crystal, Anderson Localization, Interaction, Simulation.

INTRODUCTION

Sapienza et al.[1], Schwagmann et al.[2] and Hoang et al.[3] studied that Purcell-enhancing the emission of a single dot in a photonic crystal waveguide and even reaching the strong coupling regime in such a structure[4]. This is an ideal for demonstrating photon mediated excitation transfer between distant dots. Coherent interaction between two quantum dots at subwavelength distance in a microcavity has been observed by Albert et al.[5]. At longer distance, the interaction was theoretically shown by Parascandolo and Savona[6] be finite but weak in three dimensional bulk and two dimensional[7] spatially homogeneous dielectric environments. Yao and Hughes[8] presented that ideal compromise between interaction strength and range was found for entangled states between distant quantum dots coupled to such a structure and the characteristic interaction distance was estimated by Minkov and Savona[9] to be given by $r_{12} = \frac{2v_g}{\gamma}$, where v_g is the group velocity at the excitation resonant frequency.

The residual in the fabrication process dramatically affected the slow guided modes. Niel Sen and Chaung[10] studied that two qubits to interact coherently in a controlled manner is an essential requirement for two qubit quantum gates, which are a building block of the mainstream quantum information protocol. In a semiconductor system, photons are a choice for our work, due to their weak coupling to the environment and long distance propagation. Portulupi et al.[11] presented subnanometer fabrication precision has been brought about ultra high-Q cavity designes[12] with mode volumes close to the diffraction limit as well as low loss, slow light engineered waveguides[13]. Chari et al.[14] studied that there is attenuation of signal during transmission, which limits the range of radio signals. Signal attenuation is an important factor in design of any communication system, where the losses occur. They also have presented that attenuation mechanism to wireless communication and physical oceanography are also important. Sing and Chaudhary[15] studied that symmetry breaking in the one dimensional crystal waveguide that holds a single nonlinear defect positioned on the centre line of the waveguide. When only the monopole eigen mode of the defect cavity belongs to the propagation band of photonic crystal waveguide. Two dipole resonant modes of the single nonlinear defect mode from a Kerr medium. They found that for the linear cavity the light would be coupled with the even dipole mode only to give rise to Breit-Wigner resonant peak at the eigen frequency of the cavity. Nonlinear coupling between the dipole modes may cause excitation of both dipole modes. Alam and Kumar[16] studied the impedance concept for waveguiding devices from the microwave frequency regime to optics and plasmonics. The expressions obtained were based on electromagnetic eigen modes that are excited at the interface of a structure. They observed that the impedance for the reciprocity based overlap of eigen modes. They found that applicability of simple circuit parameters ended and the impedance interpreted beyond any particular point. The unconjugated reciprocity framework setup to solve for the interface reflection of the different electromagnetic eigen modes. Faraon et al[17] and Huisman et al[18] studied the density of states of the disordered guides presented a Litshits tail below the Van Hove singularity. Topolancik et al[19] presented that Anderson localization of light, which for states close to or below the band edge cab be extremely strong, localizing the electric field over several elementary cells. The field profiles of such modes resemble those of photonic crystal cavity and both strong Purcell enhancement and cavity like vacuum Rabi splitting of a single quantum dot coupled to such a mode has been observed.

METHOD

The waveguide were formed by a missing row of holes in triangular lattice of circular holes etched in dielectric slab suspended in our waveguide. The specific parameters, relevant to InGaAs quantum dots in GaAs structures are lattice constant d=260 nm, hole radius 65 nm, slab thickness 120nm and a real part of the refractive index $\sqrt{\varepsilon_\infty} = 3.41$. In the absence of fabrication disorder, the structure presented one dimensional periodicity along the direction of the missing holes, thus the modes were folded into Bloch bands. On the main guided band in the spectral range close to the band edge. The fabrication disorder was introduced in the form of random fluctuations in the x and y positions and the radius of each hole, drawn from a Gaussian random distribution with zero mean standared deviation σ. A waveguide of length 512*a* was simulated and in the presence of disorder, its electromagnetic modes were computed by expansion on the basis of the bloch modes of the regular structure. Without disorder guided modes in the considered spectral range are losses, as they lie below the light core and thus do not radiate outside the slab. Disorder has several effects. If misses those modes with one light cone, introducing extrinsic losses, i.e. imposing a finite probability for out of plane radiation. It limits the maximum group index, which in the ideal case goes to infinity at the band edge and introduced modes that lie below the band edge of the regular structure. To quantify the quantum dot-waveguide and the effective quantum dot – quantum dot coupling, we have used Green's function formalism that we developed from Maxwell's equations for the photonic crystal with an added linear susceptibility due to the quantum dots. The effective coupling strength is written as

$$G^{12}(\omega_0) = d^2 \frac{2\pi\omega_0^2}{\epsilon_\infty \hbar c^2} . G(r_1, r_2, \omega_0)$$

where d is the dipole moment of the dot, $\in_\infty$ is the dielectric constant of the semiconductor, ω_0 is the exciton resonance frequency and $G(r_1, r_2, \omega_0)$ is the photonic Green's function at the dot positions, computed using the resolvent representation the ortho-normal set of electric field modes of the waveguide was obtained through Bloch mode expansion. The obtained results were compared with previously obtained results

RESULTS AND DISCUSSION

Figure (1) (a) shows the guided modes for considered spectral range losses and they lie below the light core and do not radiate outside the slab. Figure (1) (d) shows that modes slightly higher in frequency become more extended and presented more than one lobe and in fact provided the ideal compromise between strength and range of the dot-dot excitation transfer. We have considered two dots in the waveguide which were placed in the centre of an elementary cell and so at a distance multiple of 'a' from each other. The dipole moment 'd' was estimated from the spontaneous emission rate of the dot embedded in the bulk semiconductor which were taken as $\Gamma = 1\, ns^{-1}$. In the weak coupling regime, the Purcell enhancement factor for a single dot in the photonic crystal was related to the zero-distance coupling as

$$F_P = -2\,\mathrm{Im}\left[\frac{G^{11}(\omega_0)}{\Gamma}\right]$$

$$G^{11}(\omega_0) = \sum_m |g_m|^2 / (\omega_m - i\gamma_m - \omega_0),$$

where the sum runs over the electromagnetic field eigen modes, g_m is the coupling rate of the dot to each mode, ω_m and γ_m are the frequency and loss rate of each mode, $G^{12}(\omega_0)$ is a measure of the frequency of the oscillatory excitation transfer process between two distant dots. Figure (1) (e) shows the dependence with interdot distance of the averaged magnitude of the excitation transfer rate $\langle |G^{12}| \rangle$ for three different exciton transition frequencies $\omega_0 = 1.2980$, $\omega_0 = 1.2987$ and $\omega_0 = 1.3000$ eV, with band edge at $\omega = 1.2982$ eV and for $\sigma = 0.004a$. These plots show some deviation from an exponential law at large distances, but this is an unphysical result originating from the finite size of simulation domain. Figure (1) (f) presents detailed information about the dot-interaction for three different disorder magnitude. Figure (2) (a) shows the coupling $|G^{12}(\omega_0)|$ as a function of the dot-dot distance for $\sigma = 0.004a$ and $\omega_0 = 1.2985\, eV$. We have found that when localization is accounted the coupling decays significantly with distance but its magnitude at short distances is increased. This enhancement is due to the presence of modes localized on a hort spatial range. Figure (2) (c) shows the statistical distribution of $[G^{11}]$. The distribution exhibits a very long tail towards high values, suggesting a sizable probability of having large radiative coupling. Figure (2) (b) shows the function of ω_0 and the configuration averaged value of $[G^{11}]$ and compared with the value for which the cumulative distribution function was equal to 0.95. The obtained results compared with previously obtained results and were found in good agreement.

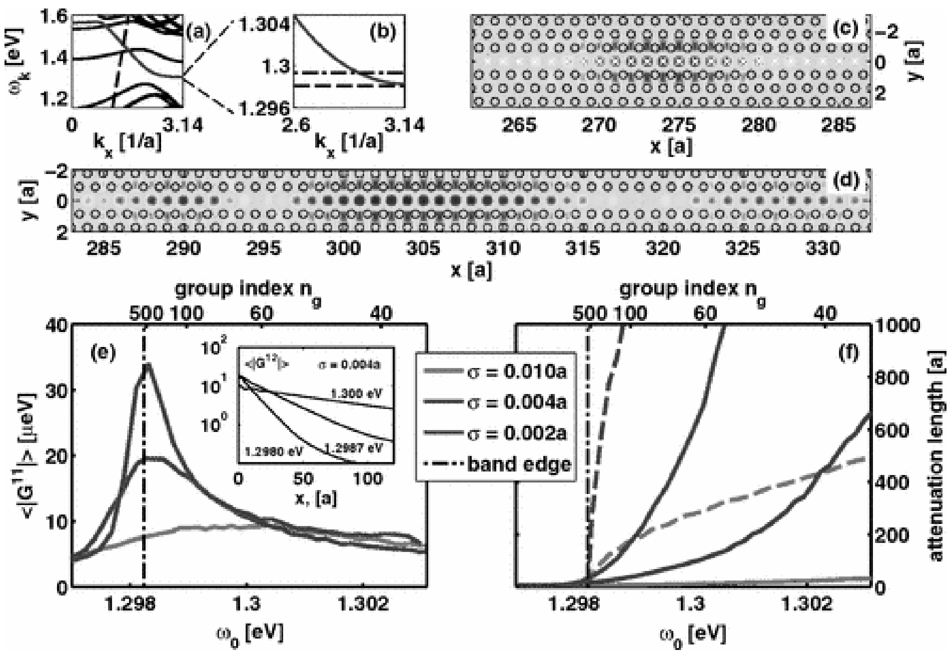

Figure 1: (a) Band structure of the regular waveguide. The dashed line represents the light cone. (b) Zoom-in close to the edge of the guided band (c) y component of the electric field (E_y)

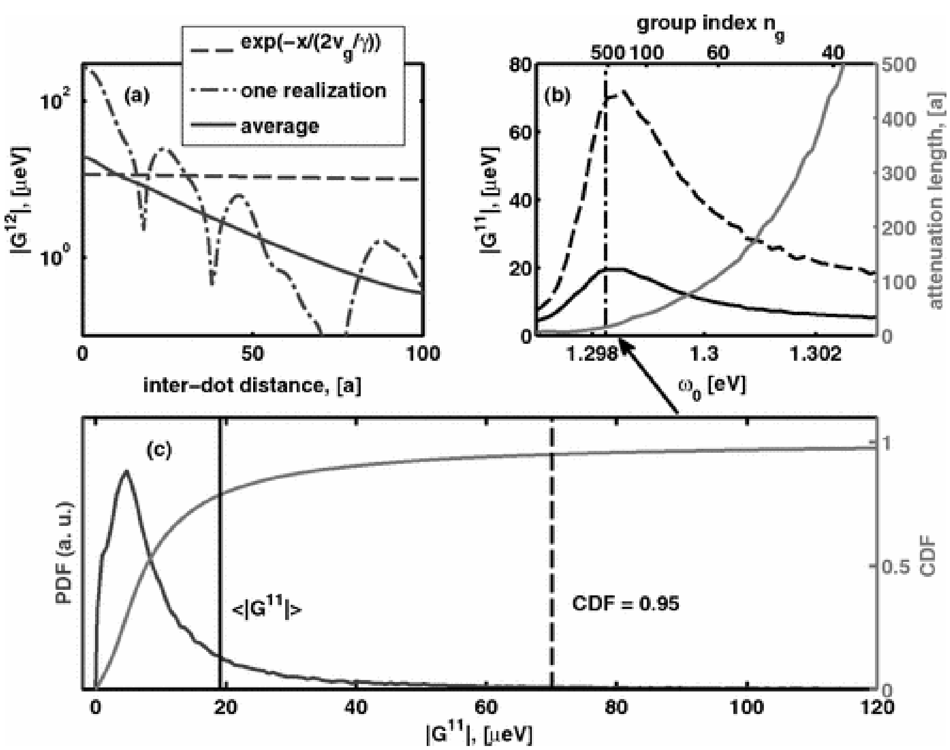

Figure 2: Excitation transfer rate vs distance without light localization (dashed) or with for a single disorder realization and the configuration average, for $\sigma = 0.004a$ and $\omega_0 = 1.2985\ \text{eV}$.

CONCLUSION

We have studied excitation transfer between quantum dots in photonic waveguides. We have presented the magnitude and range of the phonon-mediated interaction between two quantum dots embedded in a photonic crystal waveguide. We have found that disorder induced light localization has drastic effect on the excitation transfer rate. We have simulated realistic systems with different magnitudes of the disorder and have shown that while light localization has profound effect on both range and magnitude of the dot-dot excitation transfer rate. We have found that if the coupling rate exceeds the loss rates, strong coupling was set and in the case of both one and two dots the irreversible radiative decay replaced by oscillatory dynamics of the energy transfer. This is measure of the frequency of the oscillatory excitation transfer process between two distant dots. We found that the significant rage of $50\mu\mathrm{eV}$ at a range of 10 μm have been achieved in realistic systems. The obtained results were compared with previously obtained results of theoretical and experimental research works and were found in good agreement.

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