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Strong exciton-light coupling in photonic crystal nanocavities

Dario Gerace* and **Lucio Claudio Andreani**

INFM and Dipartimento di Fisica "Alessandro Volta", Università di Pavia, via Bassi 6, 27100 Pavia, Italy

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The strong coupling regime between excitons in a single self-assembled InAs quantum dot and the cavity mode in a photonic-crystal structure embedded in GaAs planar waveguides is theoretically investigated. It is concluded that zero-dimensional mixed states should form when the quality factor of the cavity mode is higher than $Q \sim 2000$. The corresponding vacuum-field Rabi splitting is close to its limiting value already for $Q \sim 10000$. Results are shown for a model GaAs-based photonic crystal nanocavity, in which single quantum dot excitons are predicted to be always in the strong coupling regime if the quantum dot is placed close to the antinode position of the electric field.

1 Introduction Photonic crystals (PhC) embedded in planar dielectric waveguides (also known as *photonic-crystal slabs*) allow for a three-dimensional (3D) control of light confinement and propagation at optical wavelengths, and are currently receiving much attention owing to the difficulties in fabricating 3D PhC with robust band gaps in the visible region (for a recent review see [1]). In PhC slabs the electromagnetic field can be confined in 3D by exploiting the photonic band gap properties in the plane of the waveguide and the confinement provided by the strong dielectric contrast along the vertical direction. By creating localized defects in the otherwise periodic structures, PhC nanocavities with cavity mode energies falling within the photonic band gap can be obtained. Very small mode volumes and ultra-high quality (Q) factors have been recently demonstrated for cavity modes in thin air-suspended Silicon slabs (also called *air bridges*) with point defects in a triangular lattice of air holes [2]. Thus, these systems appear as ideal candidates for the observation of the strong coupling regime and other interesting cavity quantum electrodynamics phenomena in photonic nanostructures.

Exciton-polaritons are the mixed states of material and electromagnetic excitations [3], and it is well established that the dimensionality of the involved particles is a crucial issue in order to observe the strong coupling regime. In particular, material excitations must be coupled to a density of photonic modes whose dimensionality is lower than or at least equal to the density of states of confined excitons (for a recent review see [4]). Exciton-polaritons have been observed in electron and photon confined systems made of QWs embedded in planar microcavities [5], where both excitons and photons are confined along one direction and obey boson statistics (for a review see [6]). The ultimate goal, that is the strong coupling between 3D confined material and radiation states, has not been reached up to now. Previous studies have shown that single self-assembled InAs quantum dot (QD) emitters in GaAs/AlGaAs pillar microcavities (or *micropillars*) are intrinsically in the weak coupling regime [7,8]. Single QDs, whose elementary excitations are those of a two-levels system and therefore have a fermionic character, should have an oscillator strength larger than 100 in order to be in the strong coupling regime in pillar microcavities [8]. Excitons localized to monolayer fluctuations in QW structures embedded in micropillars could be in the strong coupling regime [9], but this prediction has not been experimentally supported yet.

* Corresponding author: email: gerace@fisicavolta.unipv.it, Phone: +39 0382 507 680, Fax : +39 0382 507 563

In this paper, theoretical results for the radiation-matter coupling in PhC slab nanocavities are presented. The purpose is to show that the strong coupling between a single self-assembled InAs QD and the cavity mode in a GaAs-based PhC air bridge is achievable with state-of-the-art fabrication technology. The peculiar characteristics of cavity states confined in PhC slabs, such as small mode volumes and very high Q-factors, make them ideal systems for this purpose as compared to microdisks or micropillars. Calculations are shown for a GaAs PhC air bridge, in which direct observation of the strong coupling regime should be possible if the QD is placed close to the antinode of the electric field confined in the nanocavity.

2 Theory The theory of radiation-matter coupling for a single QD in a 3D photonic nanocavity relies on the Jaynes-Cummings model, where the QD is modelled as a two levels system coupled to the electric field of the cavity mode by dipole interaction. The quantum hamiltonian derived from this model has a discrete spectrum consisting in a ladder of dressed states, in which each excited state is split into two levels separated by $2\hbar\Omega_0\sqrt{n+1}$, where $\hbar\Omega_0$ is the exciton-photon coupling and n is the number of confined photons [10]. In the weak excitation regime, we can consider only the transition between the ground state and the first excited doublet, whose splitting $2\hbar\Omega_0$ corresponds to the vacuum-field Rabi splitting between the QD transition and the single cavity mode. In order to take into account the finite radiative linewidth of both the QD exciton (Γ_{ex}) and the cavity mode ($\hbar\omega_0/Q$, ω_0 being the frequency of the mode) a master-equation approach has been used, which leads to an analytical expression for the complex energy splitting of the two oscillators [8]

$$\hbar\Omega_{\pm} = \hbar\omega_{\mathrm{ex}} \pm \sqrt{\hbar^2\Omega_0^2 - \left[\frac{\Gamma_{\mathrm{ex}} - (\hbar\omega_0/Q)}{4}\right]^2} - \mathrm{i}\left(\frac{\Gamma_{\mathrm{ex}} + (\hbar\omega_0/Q)}{4}\right), \tag{1}$$

where ω_{ex} is the fundamental exciton frequency, and $\Omega_0 = (\pi e^2 f)^{1/2}/(4\pi\epsilon_0\epsilon_{\mathrm{r}} m\widetilde{V})^{1/2}$ is the Rabi frequency of the QD-cavity system in terms of the oscillator strength of the single QD (f), the effective mode volume ($\widetilde{V}$), the free electron mass (m), and the relative dielectric permittivity of the cavity material (ϵ_{r}). The effective mode volume is defined as $\widetilde{V} = \left[\int \epsilon(\mathbf{r})|\mathbf{E}(\mathbf{r})|^2 \mathrm{d}\mathbf{r}\right] / \left[\epsilon(\mathbf{r}_{\mathrm{peak}})|\mathbf{E}(\mathbf{r}_{\mathrm{peak}})|^2\right]$ [11], where $\mathbf{r}_{\mathrm{peak}}$ is the peak position of the product $\epsilon(\mathbf{r})|\mathbf{E}(\mathbf{r})|^2$, and the integral is the normalization of the electric field. In the following we will assume that the single QD is placed in $\mathbf{r}_{\mathrm{peak}}$ and that the field is normalized.

In order to calculate the resonance energy, the Q-factor, and the effective volume of the cavity mode in a PhC slab, a recently developed theoretical approach is adopted [12]. Briefly, it relies on the solution of the Maxwell equation for the magnetic field as a linear eigenvalue problem, after expansion of the field on the basis of the guided modes of an effective planar waveguide with spatially averaged dielectric constants in each layer. The coupling to radiative modes of the planar slab is treated by perturbation theory, and it leads to the imaginary part of mode frequencies in terms of the one-dimensional density of photonic states [12]. This approximate method allows to treat on the same footing both truly guided and quasi-guided modes, the latter lying above the air light line after the folding and splitting of the guided modes in the first Brillouin zone due to the periodic modulation of the dielectric constant. The intrinsic radiative linewidth of quasi-guided modes is defined as twice the imaginary part of the corresponding mode frequencies. In order to study nanocavities embedded in the PhC structure, a large supercell is used in the plane of the waveguide. The solution of Maxwell's equations for the system with supercell leads to real and imaginary parts of the cavity mode with a small wave vector dispersion. In order to smear out the supercell effects, the Q-factor is defined as $Q = \langle\omega_0\rangle / 2\langle\mathrm{Im}(\omega_0)\rangle$, where $\langle\omega_0\rangle$ and $\langle\mathrm{Im}(\omega_0)\rangle$ are averaged over the Brillouin zone defined by the supercell periodicity.

3 Results In Fig. 1(a) a schematic picture of the GaAs PhC slab nanocavity is displayed. The cavity is formed by filling three air holes along the ΓK direction of the triangular lattice; the main symmetry directions ΓM and ΓK are also defined, as well as the relevant structure parameters. In Figs. 1(b) and (c) the squared modulus of the normalized electric field is plotted along y and x, respectively. The parameters

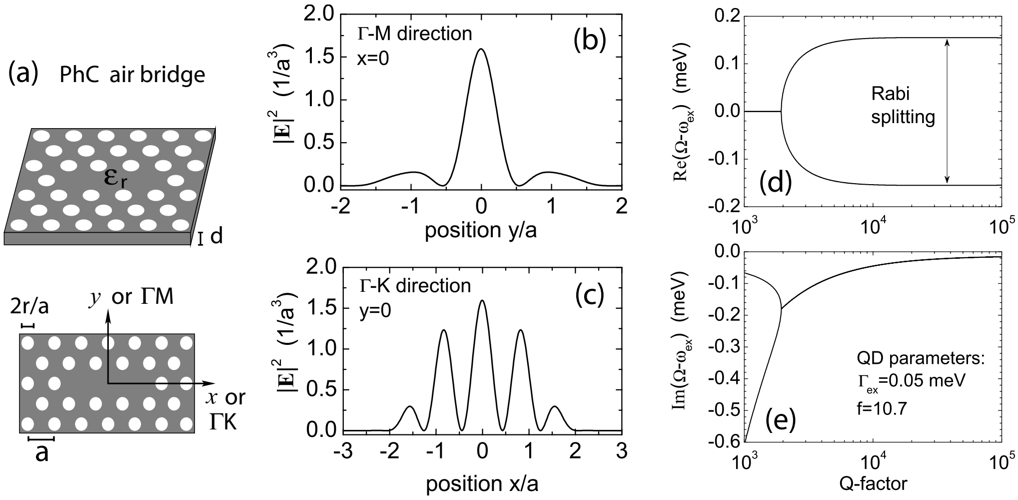

Fig. 1 (a) Schematic picture of the GaAs PhC nanocavity. The dielectric constant of GaAs at low temperature and 1.3 eV is $\epsilon_{\mathrm{r}} = 12.53$. Parameters of the structure are: slab thickness $d = 126$ nm, lattice constant $a = 258$ nm, hole radius $r/a = 0.3$; the main symmetry directions in the triangular lattice are also defined. (b) Squared modulus of the normalized electric field along y or ΓM direction at $x = 0$, and (c) along x or ΓK at $y = 0$. (d) Real and (e) imaginary parts of Eq. 1 as a function of Q-factor, for $\Gamma_{\mathrm{ex}} = 0.05$ meV, $f = 10.7$, and $V = 1.1 \times 10^{-14}$ cm^3.

of the PhC slab nanocavity are chosen in order to have the cavity mode energy at $\hbar\omega_0 = 1.3$ eV, which is typical of InAs self-assembled QDs, and are reported in the caption. The QD is assumed to be placed exactly at the center of the nanocavity, corresponding to the antinode of the field. The effective mode volume, calculated from the peak position of the normalized electric field, is $\widetilde{V} \simeq 1.1 \times 10^{-14}$ cm^3 that is about an order of magnitude smaller than in micropillars [8]. In Figs. 1(d) and (e) the real and imaginary parts of the complex splitting (Eq. 1) are plotted as a function of the Q-factor of the nanocavity. Realistic parameters for InAs QD structures are used (see caption). The oscillator strength can be estimated from the measured radiative lifetime $\tau \sim 1$ ns [7]. The crossover from weak to strong coupling is seen to appear at $Q \sim 2000$, even if the corresponding imaginary part is still larger than the Rabi splitting. The maximum Rabi splitting for this kind of systems is seen to be reached already for $Q \sim 10000$. Such values of Q are well within the reach of present-day fabrication technology [2].

In Ref. [2] a strong enhancement of the Q-factor in a PhC slab nanocavity has been demonstrated by using the principle of *gentle confinement*. The position of the two nearest holes along the ΓK direction (that is the x direction in real space) was slightly shifted in order to produce a Gaussian envelope function for the confined field. In Figs. 2(a), (b) and (c) the calculated mode energy, Q-factor and effective volume are plotted as a function of the holes' shift, $\Delta x/a$. The parameters of the PhC nanocavity are the same as in Fig. 1. The resonance energy and the mode volume do not change appreciably, while the Q-factor has a dramatic increase with a maximum $Q > 10^5$ for $\Delta x/a \sim 0.18$. The latter results are employed to calculate the complex splitting as a function of $\Delta x/a$, which is shown in Figs. 2(d) and (e). It is evident that the system is always in the strong coupling regime, regardless of the gentle confinement of the field. This result is in agreement with the calculations of Figs. 1(d) and (e), because the Q-factor is always higher than 2000 for the present nanocavity. The imaginary part of the complex splitting has a minimum for a value of $\Delta x/a$ corresponding to the maximum Q-factor. It is arguable that, in order to observe the strong coupling, shifting the holes in the PhC slab nanocavity could be of importance for reducing the emission linewidth of the two peaks. All the previous results could be experimentally verified provided that a good control over the position of the single QD emitter as well as of its emission energy is realized, which seems to be close to current technological achievements in this field [13].

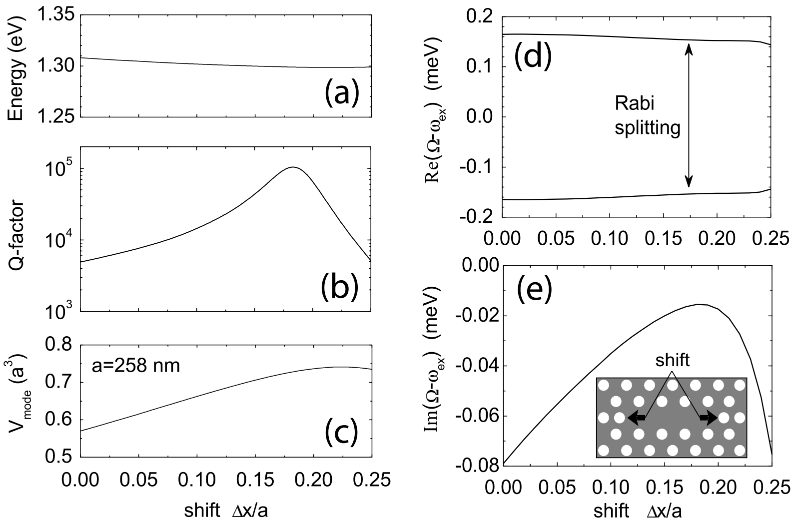

Fig. 2 Results for a PhC slab nanocavity in GaAs air bridge. Parameters of the structure are: $d = 126$ nm, $a = 258$ nm, $r/a = 0.3$. (a) Energy, (b) Q-factor, and (c) mode volume for the cavity mode as a function of the shift of two holes along the x direction. (d) Real and (e) imaginary parts of Eq. 1, plotted as a function of the holes' shift by using the quantities calculated in (a), (b), and (c), and QD parameters $\Gamma_{\rm ex} = 0.05$ meV, $f = 10.7$.

4 Conclusions A theoretical study of the strong coupling regime between a single InAs quantum dot and the cavity mode of a photonic crystal slab nanocavity has been reported. The main conclusion is that the formation of mixed exciton-light states with full 3D confinement is achievable with state-of-the-art fabrication technology of PhC slabs with high Q-factors and small mode volumes. This is more favorable than with InAs QDs in GaAs/AlGaAs micropillars, which are intrinsically in the weak coupling regime and give a radiative decay. In order to observe the strong coupling in PhC slab cavities, gentle confinement of the field can be exploited for increasing the Q-factor of the cavity mode while leaving almost unchanged its resonance energy and mode volume. Recent studies on the control of position and size of self-assembled QDs inside a PhC nanocavity [13] make these systems very promising for the first observation of such a pure quantum effect.

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