Quantitative Description of Strong-Coupling of Quantum Dots in Microcavities

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Abstract. We have recently developed a self-consistent theory of Strong-Coupling in the presence of an incoherent pumping [arXiv:0807.3194] and shown how it could reproduce quantitatively the experimental data [PRL **101**, 083601 (2008)]. Here, we summarize our main results, provide the detailed analysis of the fitting of the experiment and discuss how the field should now evolve beyond merely qualitative expectations, that could well be erroneous even when they seem to be firmly established.

PACS: 42.50.Ct, 78.67.Hc, 42.55.Sa, 32.70.Jz

Strong-Coupling (SC) is the term consecrated by the quantum optics community to designate "quantum coupling", where coherent interaction dominate over dissipation. A vivid picture represents this regime in terms of a cyclic exchange of energy between the light and matter fields (the so-called "Rabi oscillation"). This oscillation is a particular case as can be seen straightforwardly by considering two conceptual cases where it does not occur: when the system is in an eigenstate of the SC hamiltonian, in which case it has no dynamics, and when it has reached a steady state (SS), where, regardless of which quantum state is realized, energy is balanced rather than exchanged. The SS is the relevant case for many experimental configurations with semiconductors [1, 2, 3], where a continuous incoherent pumping excites the system. An anticrossing is looked for in the luminescence spectra as a proof of SC, attributed to the emergence of "dressed" states.

To compute a luminescence spectrum of a QD in a semiconductor, one must consider an innocent-looking but important consequence of pumping: it enforces a steady state that is a mixture of cavity photons and excited state of the QD (exciton). The lineshape of the cavity luminescence spectrum $S(\omega)$ depends strongly on whether the system is photon-like or exciton-like [4], in the sense of which particle would be injected in the system in the limit of vanishing pumpings that keep a fixed ratio as they go to zero. The steady state should be computed self-consistently from the interplay of pumping and decay, rather than assuming that the system is, typically, in the excited state of the QD. The latter assumption would be reasonable if there was only one kind of pumping, namely in this case an electronic pumping. However, experimental evidence seems to imply that an incoherent cavity pumping accompanies the electronic pumping [5]. The most likely reason is that beside the QD that is strongly coupled to the cavity, there are many other dots in weak-coupling, that also get excited by the electronic pumping, and that populate the cavity when they de-excite. This, for the SC dot, is perceived as an incoherent cavity pumping.

Even in the simplest description where the two modes (light, a, and matter, b) are bosonic, the luminescence spectra enjoy a wealth of subtle characteristics when incoherent and continuous pumpings $P_{a/b}$ for the cavity/exciton, are introduced. Those are discussed at length in Ref. [4]. Here we mention the most important ones: anticrossing is not systematically observed for a system in SC, depending on whether the system is more photonlike $(P_a > P_b)$, or more exciton-like $(P_b > P_a)$. More surprisingly, an "apparent" anticrossing can be observed in a system that is in weak-coupling, due to an interference that carves a hole in the spectra. These two facts together disconnect completely an anticrossing behaviour from the realization of SC. One should not, therefore, rely on this qualitative effect to ascertain SC. Instead, a fitting of the data should be attempted, so as to place a given experiment in a region of SC defining rigorously the dressed states, rather than from their ability to survive in the luminescence spectrum.

We have considered one of the pioneering experiment [1], as a test of the model, and found an excellent agreement with a linear (bosonic) model, cf. Fig. 1, provided that both cavity and exciton pumping are taken into account. This is consistent with the experimental curves that feature a strong cavity emission. In panel (b) we show how the lineshapes transform when the cavity pumping is switched off: the exciton line dominates, and no anticrossing is observed. The system is nevertheless still in SC. The confrontation of the theory with the experimental data was done for illustration only, as the raw experimental data was not available by the time of

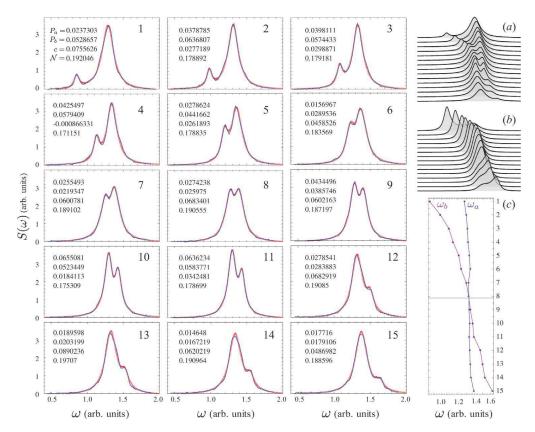


FIGURE 1. Theoretical fit (in semi-transparent red) of the data by Reithmaier *et al.* digitized from Ref. [1] (blue). The model [4] provides $S(\omega) = \frac{1}{2\pi} \text{Re} \sum_{\sigma=-1,1} \frac{1+\sigma\mathscr{C}}{\Gamma_+ + i[\sigma R + \omega - (\omega_a + \omega_b)/2]}$ with $\Gamma_\pm = (\gamma_a - P_a \pm (\gamma_b - P_b))/4$, $R = \sqrt{g^2 - (\Gamma_- + i\Delta/2)^2}$, $D = \frac{g}{2} (\gamma_a P_b - \gamma_b P_a) (i\Gamma_+ - \Delta/2)/g^2 \Gamma_+ (P_a + P_b) + P_a (\gamma_b - P_b) (\Gamma_+^2 + (\Delta/2)^2)$ and $\mathscr{C} = \Gamma_- + i(\Delta/2 + gD)/R$. The data has been fitted on rescaled axes for numerical stability by a Levenberg–Marquardt method with $\mathscr{N}S(\omega) - c$, with \mathscr{N} and c to account for the normalization and the background. Beside these two necessary parameters regardless of the model, each panel only has $P_{a/b}$ and $\omega_{a/b}$ (c) as fitting parameters. g and $\gamma_{a/b}$ have been optimized globally, with best fits for $g = 61\mu\text{eV}$, $\gamma_a = 220\mu\text{eV}$ and $\gamma_b = 140\mu\text{eV}$. (a) shows the anticrossing from curves 1–15 put together. (b) keeps all fitting parameters the same but with $P_a = 0$ and vanishing P_b . The dot emission now dominates and no anticrossing is observed, although the system is still in strong-coupling.

our investigation. We have therefore digitized the data, what forbids an in-depth statistical analysis, since the experimental points are required rather than the interpolated curves published in Ref. [1], if only to know the numbers of degrees of freedom. Note that one expects better still results as our procedure added noise. We found the best agreements near resonance, which might be due to the exciton that, when it is less-strongly coupled at larger detunings, may go below the resolution of the detector, resulting in an apparently broader line. All these limitations can be circumvented with a careful statistical analysis (and treatment of the data to reconstruct linewidths below the experimental resolution). This is a standard procedure of a mature field to validate a theoretical model over another by statistical analysis of the experiment. Nullifying hypotheses such as: "a Fermi (two-level) system accounts for the observed data better than a Boson model" are important to assess the achievements made in terms of quantum emitters with these systems. This would also provide a meaningful and quantitative comparison between the various implementations (micropillars, microdisks and photonic crystals). Lacking the full experimental data, we have merely been unable to provide a confidence interval to our most-likelihoods estimators. Doing so, progress will be meaningfully quantified, and claims—rather than ranging between likely and convincing—will become unambiguously proven (within their interval of confidence).

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