Single and two photon emission from a semiconductor quantum dot in an optical microcavity

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Abstract. We calculate the single and two photon emission from a cavity containing quantum dot incoherently pumped. Results for correlation functions and the entanglement visibility of linearly polarized photons are presented.

A quantum dot (QD) embedded in a microcavity can be an efficient emitter of single and two photons when the lower energy excitations of the QD (usually labeled as excitons) are close to resonance with a mode of the optical cavity. The precise problem addressed in this work is the possibility of emitting pairs of correlated photons with a efficiency higher than that of emitting single photons. The kind of correlation we are interested in is that of the polarizations of the two photons in the pair. This can be addressed by making a Hambury-Brown Twiss (HBT)-like experiment measuring linearly polarized photons at the two beams of the HBT set-up. Our figure of merit is the entanglement visibility, defined below, which gives information about the availability to store information in the relative angle between the linear polarizations of the two photons.

In this work we consider just four levels of the QD: the ground state G, the two excitons $X+$, $X-$ with third component of their angular momentum equal to ± 1 and the biexciton B. The optical modes of the cavity can have right R or left L circular polarization. We consider only a single frequency ω_C for the modes which are coupled, with intensity g, to the QD excitations. The system can emit either cavity photons with a rate κ or leaky modes, with a rate γ, produced by spontaneous transitions between the QD states. An essential ingredient of our model, not considered before [1], is an incoherent pumping (either optical or electrical), with rate P, obviously necessary in any experimental situation. The main consequence of such pumping is the lack of any upper restriction in the number of photons inside the cavity.

The magnitudes of experimental interest are obtained from first $G^{(1)}_{R/L}(t,t') = \langle a^\dagger_{R/L}(t')a_{R/L}(t)\rangle$ and second $G^{(2)}_{R/L,R/L}(t,t') = \langle a^\dagger_{R/L}(t)a^\dagger_{R/L}(t')a_{R/L}(t')a_{R/L}(t)\rangle$ order correlation functions, or their Fourier transforms, where $a^\dagger_{R/L}$ and $a_{R/L}$ are the creation and annihilation operators for cavity photons with R/L polarizations. These two-times correlation functions can be obtained, by using the quantum regression theorem, from the dynamics of the density matrix. We have computed such dynamics by means of a master equation within the usual rotating wave and Born-Markov approximations and tracing out the pumping and emission degrees of freedom. From the practical point of view this imply to solve numerically, by means of a Runge-Kutta method, a set of a few thousands differential equations[2, 3].

The probability of emitting pairs is proportional to $G^{(2)}$. We are interested in studying a HBT-like experiment with linearly polarized photons described by operators $a_\theta = \cos\theta(a_R + a_L)/\sqrt{2} + i\sin\theta(a_R - a_L)/\sqrt{2}$. Here, we will give only results for the case of no delay ($t = t'$), so that we need the second order correlation function

$$G^{(2)}_\theta = \langle a^\dagger_0 a^\dagger_\theta a_\theta a_0\rangle = \frac{G^{(2)}_{R,R}}{2} + G^{(2)}_{R,L}\cos^2\theta. \quad (1)$$

where we have taken the linear polarization of one the beams as origin because the correlation function only depends on the relative phase θ of the two polarizations. Since $G^{(2)}_\theta$ is a function of the continuous unknown θ, the range of values than can be covered is given by the entanglement visibility

$$\mathscr{V} = \frac{\max G^{(2)}_\theta - \min G^{(2)}_\theta}{\max G^{(2)}_\theta + \min G^{(2)}_\theta} = \frac{G^{(2)}_{R,L}}{G^{(2)}_{R,R} + G^{(2)}_{R,L}}. \quad (2)$$

We present results for the following parameters: The coupling is $g = 1meV$ and the leaky emission rate $\gamma = 0.1meV$. The two excitons are taken as degenerate with detunings $E_X - E_G - \hbar\omega_C = \hbar\omega_C - (E_B - E_X) = 5meV$.

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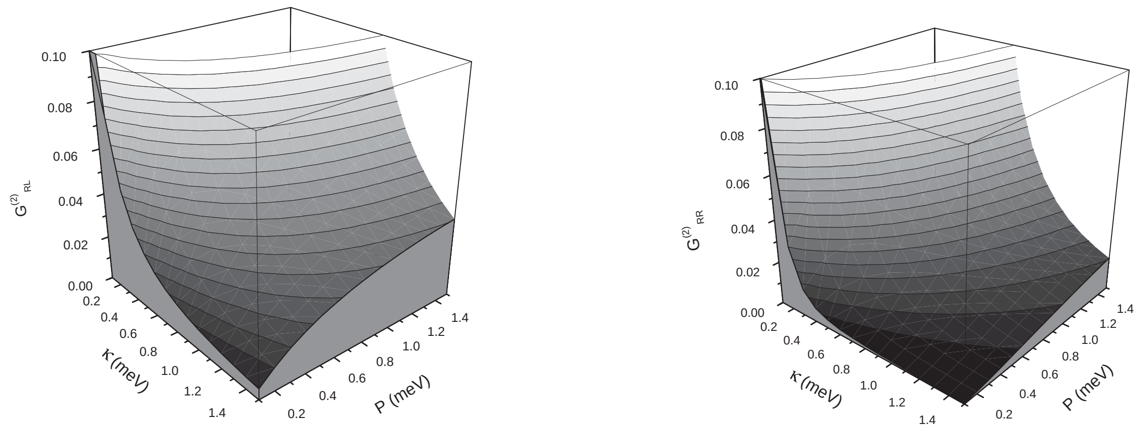

FIGURE 1. Correlation functions $G^{(2)}_{R,L}$ and $G^{(2)}_{R,R}$ as a function of the rates for pumping P and cavity photons emission κ.

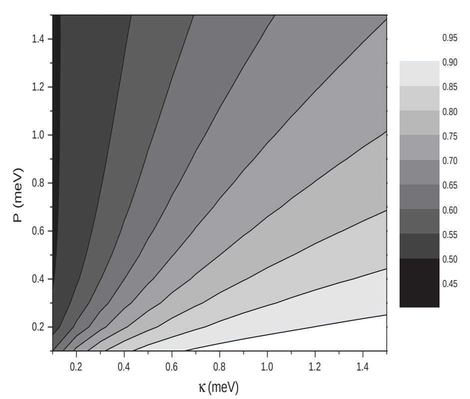

FIGURE 2. Visibility $\mathscr{V}$ as a function of the rates for pumping P and cavity photons emission κ.

Figure 1 shows $G^{(2)}_{R,R}$ and $G^{(2)}_{R,L}$ while figure 2 shows $\mathscr{V}$. In both figures, results are given as a function of the pumping P and emission rate κ. In figure 1, the region for low κ and high P corresponds to a correlation function monotonously increasing from 0.1 up to 14. Our results show that a high visibility is only obtained in the region of low P and large κ. When the system is poorly pumped and it emits efficiently, the population of photons inside the cavity is low. It is improbable to have two photons with same circular polarization in the cavity[3]. Therefore, $G^{(2)}_{R,L} >> G^{(2)}_{R,R} = G^{(2)}_{L,L}$ implying, in Eq. (2), a large $\mathscr{V}$. It must be pointed out that in the region of large visibility, $G^{(1)} > G^{(2)}_{\theta}$ so that the emission of single photons is more efficient than that of pairs. Moreover, these correlation functions produce a second order coherence function $g^{(2)}(t=t')$ smaller than 1 which means a sub-Poissonian distribution of squeezed photons.

We have performed calculations for many other cases not presented here. In particular for a situation in which the two excitons $X+$ and $X-$ are not degenerate. The results are qualitatively similar to the ones shown here. Moreover, we have also calculated correlation functions at finite delay ($t' > t$). Finally, we have also computed the spectrum of the emitted light. As expected, it is dominated by the emission at the cavity photon frequency but it also shows non negligible features close to $E_B - E_X$ and $E_X - E_G$ due to the strong coupling between the cavity mode and the QD excitations.

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