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Photon statistics of radiation emitted by two quantum wells embedded in two optically coupled semiconductor microcavities

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ABSTRACT

We study theoretically the photon statistics of the field emitted from two optically coupled semiconductor microcavities each containing a quantum well. The emission is determined by the interplay between exciton-photon coupling in each quantum well and internal interaction between the two optically coupled microcavities. A high degree of coherent control and tunability via the quantum well-cavity coupling strength and photon tunneling over the photon statistics of the transmitted field can be achieved. We demonstrate that the optical property of radiation emitted by one quantum well can be controlled by the properties of the second quantum well. This result has the potential to be used in quantum information processing. We show that the exciton-photon coupling influences the polariton resonances in the intensity spectrum of the transmitted field. The results obtained in this investigation has the potential to be used for designing efficient controllable all-optical switch and high sensitive optical sensor.

1. Introduction

Optical properties of semiconductor nanostructures like quantum wells (QW) and quantum dots (QD) offer many new fascinating features [1–9] with potential applications in optoelectronic devices [1]. In this regard, the formation of an electron-hole pair termed as exciton plays a crucial role. The exchange of energy between the excitons and the vacuum field is attributed to the observed quantum optical response of QW and QD. The interaction of an exciton in a QW with optical modes of a micro-cavity has been studied extensively in the past [10–14]. In semiconductor nanostructures embedded in micro-cavities, such coherent exchange of energy becomes observable as vacuum Rabi splitting in the strong coupling regime [15–22]. A strong coupling is achieved when the exciton-field coupling strength is much larger than the relaxation rates of the medium and of the cavity [9,23]. The coherent energy exchange between excitons and photons can be explained as the formation of polaritons which are the mixed modes of QW exciton and cavity photon [18,24,25]. QW and QD embedded in photonic crystal cavities are considered highly attractive candidates for implementing optoelectronic devices such as an all optical switch [26–32] which has been demonstrated in recent experiments [33,34]. To make such optoelectronic device a reality, complete coherent control of the quantum device is essential. In light of these interesting quantum optical features associated with semiconductor nanostructures in microcavities and possible new optoelectronic applications, we investigate in the current paper a relevant question: How is the quantum optical property of the radiation emitted from a QW in a semiconductor micro-cavity affected in the presence of a second QW? At the heart of quantum information processing is conditional quantum dynamics, where measurements made on one quantum system is controlled by the quantum state of another system. Such conditional dynamics in interacting quantum dots have been realized experimentally [35]. In particular, we will

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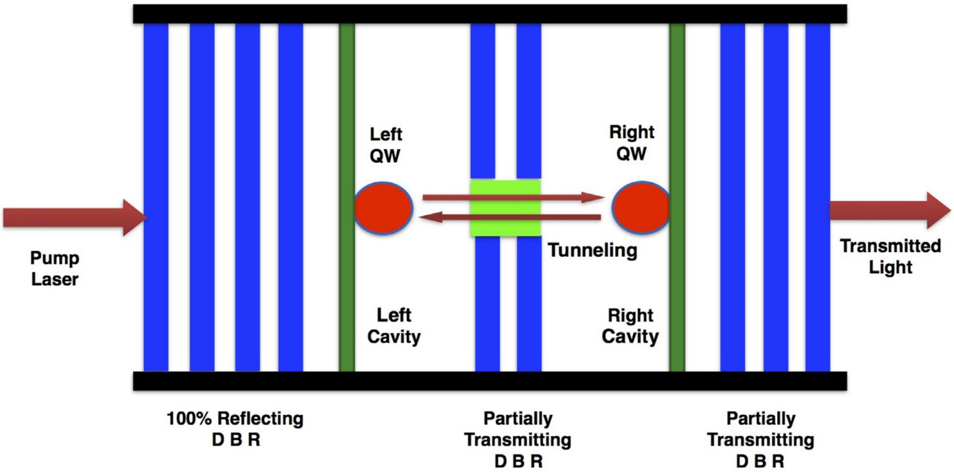

Fig. 1. Schematic representation of the setup studied in the text. It consists of two semiconductor micro-cavities made up of distributed Bragg reflectors (DBR) as shown. The left micro-cavity is driven by a strong pump laser. Both the cavities confine a quantum well each which is coupled to the respective field mode. The two micro-cavities are optically coupled via the tunneling of photons between the two cavities. The blue and white strips correspond to AlGaAs and GaAs layers respectively.

investigate the radiation emitted from two micro-cavities each containing a QW. The two micro-cavities are coupled due to photon tunneling. We will investigate the steady state mean cavity photon number, the dynamical evolution of the intensity of fluorescent light and the intensity spectrum of the transmitted field. To this end, we will be using both analytical as well as numerical tools.

2. System Hamiltonian and steady state

We consider a system consisting of two coupled micro-cavities, each containing a single semiconductor quantum well and supporting a field mode as shown in Fig. 1. Experimentally our proposed system could be InAs quantum well in GaAs semiconductor micro-cavity. These cavities are formed with the help of a set of distributed Bragg reflectors (DBR). In addition to this, photons are injected into the left cavity through an external pump. Photons are able to tunnel between these two cavities. Thus the right cavity is driven by the output optical field from the left cavity. The field modes of the two micro-cavities thus constructed are coupled to the exciton mode of their respective QW, i.e. the left micro-cavity mode is coupled to the left QW exciton mode while the right micro-cavity mode is coupled to the right QW exciton mode.

An exciton in the QW can be considered as a quasi-particle resulting from the interaction between one hole in the valence band and one electron in the conduction band. In the weak excitation regime, where the density of the excitons is sufficiently low, the interaction between the excitons due to coulomb interaction is extremely weak and thus can be ignored. We can treat the exciton as a composed boson when the exciton radius is significantly smaller than the average separation between neighbouring excitons. The left cavity is driven at rate $\lambda = \sqrt{\frac{2P\kappa_L}{\hbar\omega_p}}$ through the left DBR by a laser with frequency ω_p and power P. The left cavity decay rate is κ_L. The pump is assumed to excite a single mode of the left cavity with frequency ω_L. The coupled exciton-optical system is described by the Hamiltonian in a frame rotating with the pump frequency ω_p as,

$$\begin{aligned} H= \quad & \Delta_L a_L^\dagger a_L + \Delta_R a_R^\dagger a_R + \Delta\Omega_1 c_L^\dagger c_L + \Delta\Omega_2 c_R^\dagger c_R + J(a_L^\dagger a_R + a_R^\dagger a_L) \\ & + iG_1(a_L^\dagger c_L - c_L^\dagger a_L) + iG_2(a_R^\dagger c_R - c_R^\dagger a_R) + i\lambda(a_L^\dagger - a_L) \end{aligned} \tag{1}$$

Here a_L and a_R are the annihilation operators for a photon in the left and right micro-cavity respectively. The operators c_L and c_R are the annihilation operators for an exciton in the left and right QW respectively. Here $\Delta_L = \omega_L - \omega_p$, $\Delta_R = \omega_R - \omega_p$, $\Delta\omega_1 = \omega_1 - \omega_p$ and $\Delta\omega_2 = \omega_2 - \omega_p$. The left and right cavity frequencies are ω_L and ω_R respectively while ω_1 and ω_2 are the left and right exciton mode frequencies respectively. The fifth term in the Hamiltonian (Eq.1) describes the tunneling of the cavity photons between the two cavities with J as the tunneling constant. The sixth and the seventh terms in the Hamiltonian describes the linear exciton-photon interactions with exciton–photon interaction strengths G_1 and G_2 for the left and right QW excitons respectively. The last term describes the strong pump of amplitude λ.

Using the Hamiltonian (1) and taking into account the dissipation processes, one obtains the following quantum Langevin equations:

$$\frac{da_L}{dt} = -(i\Delta_L + \kappa_L)a_L - \mathrm{i}\,Ja_R + G_1 c_L + \lambda + \sqrt{2\kappa_L}\,a_L^{\mathrm{in}}, \tag{2}$$

$$\frac{da_R}{dt} = -(i\Delta_R + \kappa_R)a_R - \mathrm{i}\,Ja_L + G_2 c_R + \sqrt{2\kappa_R}\,a_R^{\mathrm{in}}, \tag{3}$$