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RESEARCH ARTICLE

Photon properties of light in semiconductor microcavities

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Abstract Properties of atom-like emitters in cavities are successfully described by cavity quantum electrodynamics (cavity-QED). In this work, we focus on the issue of the steady-state and spectral properties of the light emitted by a driven microcavity containing a quantum well (QW) with the excitonic interactions using simulation of fully quantum-mechanical treatment. The system is coherently pumped with laser, and it is found that depending on the relative values of pumping rate of stimulated emission, either one or two peaks close to the excitation energy of the QW or to the natural frequency of the cavity are shown in the emission spectrum. Furthermore, the nonclassical proprieties of the emitted photon have been investigated. This excitonic system presents several dynamical and statistical similarities to the atomic system, in particular for the bad-cavity and good-cavity limits. The results show that the photon emission can be significantly amplified due to the coupling strength between a single emitter and radiation field in the microcavity, and it is concluded that the present semiconductor microcavity system may serve as a QW laser with low threshold.

Keywords quantum well (QW), photon, exciton, exciton-photon interaction, microcavity

1 Introduction

The quantum properties of the light emitted from semiconductor cavities containing quantum dots (QDs) or quantum wells (QWs) coupled to a single mode of the electromagnetic field of an optical resonator have gained considerable interest in the context of quantum electrodynamics (QED), and have been investigated both for fundamental aspects [1–7] and for potential applications [8–30]. Phenomena which are linked to QED [2,5–22], such as Rabi splitting, have been observed in semiconductor microcavities [1,6–19,31].

In the past few years, cavity-QED effects and the regime of strong coupling between the exciton and discretized cavity modes have been achieved in semiconductor heterostructure systems based on pillar microcavities [1,5,7,10], and in microdisks [6,8,16,17], because they permit the realization of solid state cavities in which atom-like emitters in the form of QDs or QWs can be embedded. In all these structures, cavity-QED effects of zero-dimensional electron systems interacting with optical modes, like the Purcell effect or Rabi splitting, have been observed [1,5–14,16,31]. In 1999, Pelton and Yamamoto first proposed the laser with a single quantum dot as a novel ultralow threshold device, consisting of a single InAs/GaAs self-assembled QD coupled to a high finesse microsphere cavity [15]. The device would also be a model cavity-QED system, consisting of a single oscillator coupled to a single photon mode. In this sense, it is analogous to the single-atom maser, the single-atom laser [14,25,29]. Furthermore, they demonstrated that such an arrangement allows the laser threshold condition to be satisfied. The corresponding threshold current should be several orders of magnitude lower than is currently possible in semiconductor lasers. The strong-coupling regime and the Rabi splitting for a single GaAs QD inserted in a microdisk cavity has been observed [6,16]. Furthermore, in 2006 we have proposed and examined a laser device model based on a single semiconductor QD gain emitter in a passive microcavity, the microdisk, which is used to couple light from the QD emitter source, and provide enhanced spontaneous emission and feedback [8]. The results have shown that the photon-exciton coupling mode would lead to a high intensity of the single QD microcavity laser with low-threshold. It is demonstrated that the long-sought solid state implementations of the strongly coupled cavity-mode-two-level-emitter systems

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are feasible by using single QD in high-Q cavity with small mode volumes. However, the exciton-photon coupling effects with exciton-exciton scattering interactions have not been investigated thoroughly thus far.

Recently, theoretical and experimental studies brought the proof of squeezing in semiconductor microcavities with QWs [2,16–19,26]. To our knowledge, Eastham et al. [26] studied the quantum statistical proprieties of light emitted by a cavity injected with a squeezed vacuum, where the excitonic interaction was neglected. The Paris group works [2,18] dealt with the autocorrelation function of a cavity-emitted field in the case of weak excitation pumping regime and strong coupling regime. They have investigated the photon statistics in the light emitted by a semiconductor microcavity containing a QW. An analytical expression of the light-emitted autocorrelation function in the weak pumping regime has been derived, where the excitonic interaction was included [2,18].

In this work, we shall focus on the issue of the photon properties of light from a semiconductor cavity with the excitonic interactions. We will work out the steady-state and spectral properties of the light emitted from a semiconductor microcavity containing a QW with the excitonic interactions, in the regimes of weak pumping and strong pumping. The paper is organized as follows. In the next section, we describe the model and derive the master equation. Section 3 deals with the simulation results. Conclusion is in Sect. 4.

2 Model and simulation

As a specific illustration, the considered system is a semiconductor microcavity made of a set of Bragg's mirrors, as proposed in Ref. [2]. The internal two sides of the Bragg's mirrors are separated by a distance which is of the order of the wavelength λ. Inside the microcavity there is a QW localized in a position which corresponds to most of the electromagnetic field. This system is coherently driven with a laser field E.

Given sufficient coupling interaction between the QW and the electromagnetic field in the microcavity, light emission is either promoted when it resonates with a cavity eigenmode, or suppressed when it is off-resonant. The lasing transition is from an excited conduction band state to a lower conduction band state. The electron in the lower state must be removed to maintain inversion and eliminate state filling [8]. The electromagnetic field can excite an electron of the valence band to the conduction band by creating a hole in the valence band. The electron and the hole interact by giving excitonic states [5–11,16–23,31]. For this reason we take into account only this state for the exciton-photon interaction. The photonic and excitonic modes are quantified along the normal direction to the microcavity. Invariance by translation implies that the excitons with parallel wave vector $K_{//}$ can couple only with photons with parallel wave vectors $k_{//} = K_{//}$. This work deals only with the case of normal incident pumping mode irradiating the microcavity. Here the cavity reduces the spontaneous emission lifetime of the radiative transition, increasing the spontaneous emission rate. We take all parameters in this work to be scaled by γ to make them dimensionless. For excitonic spontaneous decay rate, we have taken $\gamma = 1$.

Applying the standard methods of the quantum theory of damping, the master equation in the general Lindblad form can be governed by the rotating frame [8,18–30]:

$$\frac{\partial}{\partial t}\rho = \frac{1}{\mathrm{i}\hbar}\left[\hat{H},\rho\right] + L_{\mathrm{diss}}\rho = L\rho. \quad (1)$$

The effective Hamiltonian for the exciton-photon coupling system in the cavity in the dipole and rotating-wave approximation is described by

$$H = \hbar\omega_{\mathrm{c}}a^{+}a + \hbar\omega_{0}b^{+}b + \mathrm{i}\hbar g(a^{+}b - ab^{+}) + \hbar\alpha b^{+}b^{+}bb + \mathrm{i}\hbar E(e^{-\mathrm{i}\omega_{\mathrm{L}}t}a^{+} - h.c.), \quad (2)$$

where the photon creation and annihilation operators for electromagnetic fields of microcavity are a^{+} and a, respectively; and the exciton creation and annihilation operators are b^{+} and b, respectively; ω_0 is the transition frequency of the excitonic mode; ω_{c} is the cavity resonant frequency; ω_{L} is the frequency of the pumping field; E is the amplitude of the pumping laser, and the coupling constant of the exciton-photon interaction is thus given by [5,8,16–22]

$$g = [e^{2}f/(4\pi\varepsilon_{0}\varepsilon_{r}mV)]^{1/2},$$

where f is the exciton oscillator strength, V is the effective modal volume, m is the free electron mass, e is the electron charge, and $\varepsilon_0\varepsilon_r$ is the dielectric constant. The parameter α, which represents the strength of the excitonic interaction, has the following expression [23]:

$$\alpha = \frac{3a_{\mathrm{ex}}E_{\mathrm{ex}}}{S}, \quad (3)$$

where S is the quantization area; a_{ex} and E_{ex} represent respectively the two-dimensional excitonic Bohr radius and binding energy. The fourth term describes the exciton-exciton scattering due to Coulomb interaction. It should be noted that the exact value of the nonlinear excitonic parameter which describes the strength of the interaction between excitons can be estimated [2,4,20]. Here we have taken the excitonic interaction parameter $\alpha = 0.1$.

The dissipations lead to nonunitary evolution given by [8,24–30]

$$L_{\mathrm{diss}}\rho = -\frac{\gamma}{2}(b^{+}b\rho + \rho b^{+}b - 2b\rho b^{+}) - \kappa(a^{+}a\rho + \rho a^{+}a - 2a\rho a^{+}), \quad (4)$$

where the excitonic spontaneous emission with the rate γ as well as the cavity decay with the rate κ are included. Thus, the matrix equations of motion for the microcavity system with a QW governed by the master equation are given by

$$L\rho = \frac{1}{\mathrm{i}\hbar}\left[\hat{H},\rho\right] + \sum_{k=1}^{2}\left(C_k\rho C_k^{+} - \frac{1}{2}C_k^{+}C_k\rho - \frac{1}{2}\rho C_k^{+}C_k\right), \quad (5)$$

where $C_1 = \sqrt{2\kappa}a$; $C_2 = \sqrt{\gamma}b$. We solved the density matrix differential Eq. (5) using the quantum trajectory simulation [8,28–30].

3 Result and discussion

In Fig. 1, we plot mean photon number $\langle n\rangle$ in a microcavity versus pump strength E for different coupling g. Furthermore, mean photon number $\langle n\rangle$ in a microcavity versus pump strength E and coupling strength g is shown in Fig. 2. Here, we find that $\langle n\rangle$ increases as the pump strength E is increased. The reason is that the coherent pump increases the coherence between the laser levels. This property behaves similarly to the one-atom laser [14,25,29,30]. It is seen that decreasing κ increases the intracavity photon number, which also behaves similarly to the one-atom laser [14,25,29,30]. The photon bottleneck is essentially broken up by resonance emission due to the coupling interaction. When the cavity field leads to much more photons than alone via excitonic spontaneous emission, we essentially turn the emitter into a lasing object in analog to one-atom laser. We also find that it has something in common with microlasers, and a reduction of spontaneous emission into the lasing mode. Here, we are

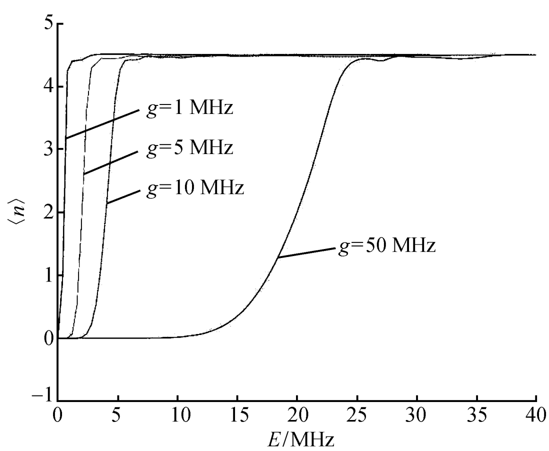

Fig. 1 Mean photon number $\langle n\rangle$ versus pump strength E for various values of g with excitonic interaction parameter $\alpha = 0.1$ and $\kappa = 1$ MHz

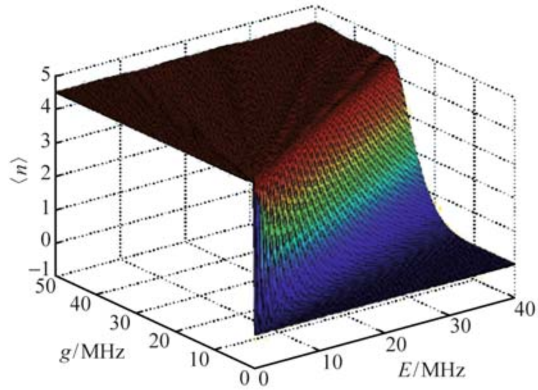

Fig. 2 Mean photon number $\langle n\rangle$ versus pump strength E and coupling strength g for $\kappa = 1$ MHz with excitonic interaction parameter $\alpha = 0.1$

only interested in the steady state properties. In this case it is possible to derive a semiclassical approximation for the mean photon number and the laser inversion in steady state, if the semiclassical factorization of the density matrix is used for larger photon numbers. For this case, the inversion Δ_{inv} is given by

$$\Delta_{\mathrm{inv}} = \sum_{n=0}^{\infty}\left(\langle n,e|\rho|n,e\rangle - \langle n,g|\rho|n,g\rangle\right). \quad (6)$$

Semiclassically, a laser is said to be at threshold when the pumping strength is just sufficient for photon production to balance the losses. This happens when sufficient population inversion and consequently net stimulated emission are achieved. Meanwhile, the threshold can be redefined following Pelton and Yamamoto [15]. Laser threshold is reached if the mean number of photons in the lasing mode is one. At this point, stimulated emission overtakes spontaneous emission, and linear amplification is replaced by nonlinear laser oscillation. As can be seen from Fig. 2, threshold can be reached for all values of κ considered. This means the present semiconductor microcavity system serves as a QW laser with low threshold.

We calculated the spectrum of the present system, which is defined as

$$S(\omega) = \int_0^{\infty}\cos(\omega t)g^{(1)}(t)\mathrm{d}t, \quad (7)$$

with the normalized first-order correlation function

$$g^{(1)}(t) = \frac{\langle a^{+}(t)a\rangle}{\langle a^{+}a\rangle} = \frac{\mathrm{Tr}\{a^{+}e^{Lt}a\}}{\mathrm{Tr}\{a^{+}a\rho\}}. \quad (8)$$

Figure 3 shows the photon emission spectra versus detuning frequency as an overview for various values of the coupling strength g and the coherent pump field E, which reveals the positions of the peaks in the emitted photon spectra. The spectra contain one narrow peak at

$\Delta = \omega - \omega_L \cong 0$, as shown in Figs. 3(a) and 3(b). This corresponds to the Rabi oscillation. An increase of the coupling g increases the mixing between the excitonic and photon modes. Also, two peaks will exist and become more and more pronounced with positions at $\Delta = \pm g(\sqrt{2}-1)$. For smaller pump E, the peak sidebands are pushed to larger frequencies as shown in Fig. 3(b). With a nonvanishing pump rate, the peaks are not only broadened, but also shifted. If the coherent pump is further increased, the narrow coherent peak arises on top of the spectrum. In this region, the photon emission is strongest and this peak dominates the spectrum. This behavior is due to the fact that with increasing coherent pump the number of photons in the microcavity mode decreases. It is concluded that depending on the relative values of pumping rate of stimulated emission, either one or two peaks close to the excitation energy of the QW or to the natural frequency of the cavity are observed in the emission spectrum.

Next, we consider the statistical properties of photons. Independently of the excitonic nonlinearity interaction coefficient α, the autocorrelation function

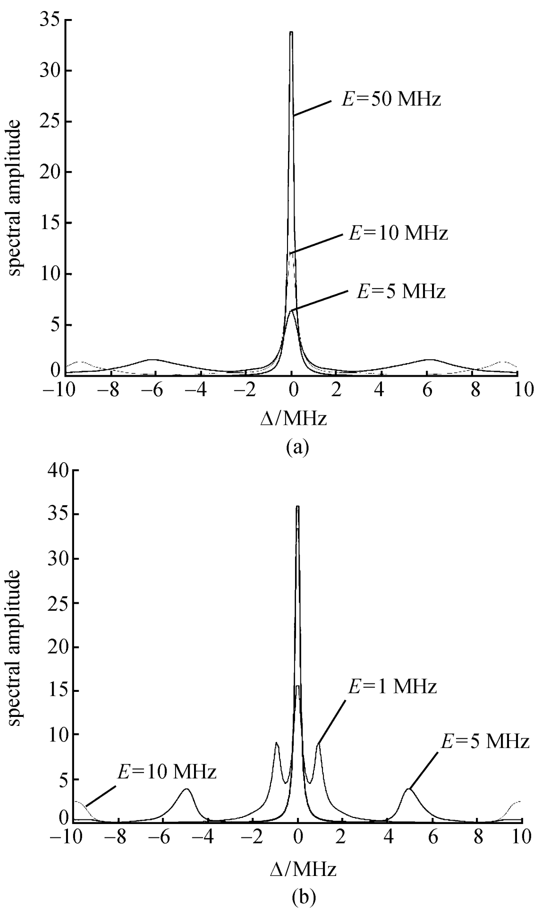

Fig. 3 Power spectral $S(\omega)$ versus detuning frequency $\Delta = \omega - \omega_L$ for various coherent pump strength E. (a) $g = 1$; (b) $g = 10$

$$g^{(2)}(\tau) = \lim_{t\to\infty} \left\langle a^{+}(t)a^{+}(t+\tau)a(t+\tau)a(t)\right\rangle$$

presents photon antibunching or photon bunching. In order to understand the physical interpretation, two physical limits can be studied. The first limit corresponds to where the cavity is very good ($\kappa/\gamma \to 0$), and we have only an antibunching effect. For the case of good cavity, the antibunching effect in excitonic system is small and disappears for $\kappa/\gamma \to 0$. A reduction in antibunching is not surprising for a better cavity, as the field fluctuations are essentially averaged out. This behavior is similar to the atomic case [2,14,25–30], which Eleuch has obtained [2]. The second limit corresponds to where the cavity is very bad, and the system has two photon statistical regimes (bunching and antibunching). In the bad-cavity limit, both atomic and excitonic systems exhibit photon antibunching. This antibunching effect disappears totally for $\kappa\gamma \gg g^2$. Therefore, we can conclude that the statistics of the emitted field from a single atom in a resonant cavity and from the excitonic cavity system are totally similar. Furthermore, the result is the determination of a range of parameters in which a state of cavity modes with Poissonian or sub-Poissonian (nonclassical) statistics can be built up within the microcavity. However, there is a small difference that should be mentioned. In the case of vanishing interaction between excitons ($\alpha = 0$) the emitted field statistics is Poissonian, which Eleuch has obtained [2,18].

4 Conclusion

In summary, we have used numerical simulations to investigate the steady-state and spectral properties of the emitted light from driven semiconductor microcavities with excitonic interactions. The system is pumped coherently with laser, and the strong coupling enhances the excitonic emission process, providing more photon emission and making it essentially a lasing object that is effectively pumped. It is found that depending on the relative values of pumping rate of stimulated emission, either one or two peaks close to the excitation energy of the QW or to the natural frequency of the cavity are observed in the emission spectrum. Furthermore, the nonclassical proprieties of the emitted photon have been investigated, and it is concluded that this excitonic system presents several statistical similarities to the atomic system, in particular for the bad-cavity and good-cavity limits in the weak laser amplitude regime, which are in agreement with the analytical results given by Eleuch. Finally, these results indicate that the present semiconductor microcavity system may serve as a QW laser with low threshold.

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