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Emission of an interacting quantum dot system embedded in an optical microcavity

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ABSTRACT

In this work, we study the emission of an interacting quantum dots system embedded in an optical microcavity. We use a model that describes the quantum dots as two-level systems interacting through the Von Foerster mechanism, and also coupled to the cavity modes. Hamiltonian and dissipative dynamics are calculated for systems of microcavity-quantum dots with different spatial configurations, given by geometric arrangement of the quantum dots in the sample. Moreover, we obtained both first and second order correlation functions and the corresponding emission spectra. The results show that the statistical properties of the emitted light by a microcavity quantum dots system, are susceptible to the spatial configuration of the dots in the sample.

1. Introduction

The study of the interaction between radiation and matter at low energies or small scales is currently a very interesting and promising field of work [44,14,42], as the understanding of this class of systems opens possibilities for applications such as the manipulation of information and computing at the quantum level [23,1,3,28]. On the other hand, the theoretical and experimental study of microcavities [31] systems and quantum dots has been increasing in recent decades [4,34], due to advances in growth and control techniques of semiconductor heterostructures [43,12], allowing the development of optical microcavities that may contain active media inside, such as quantum dots [5,41,16,21,33]. This in turn has made possible the study of the interaction between matter excitations (excitons) and light [37,45,28,10].

So because of the potential applications and to progress in manufacturing techniques of microcavity quantum-dots systems [38], it becomes important to understand and manipulate these physical systems through theoretical studies [36], in our case, that can contribute to knowledge of them and so promote possible technological applications that require these systems as feedstock [24]. These systems are formed by semiconductor nanostructures that are known as quantum dots[1] which are characterized by having discrete energy spectra similar to atoms [29]. Generally, the quantum dot densities of these systems are very high[2] [11,9] and due to their proximity the quantum dots can interact exchanging excitons between them [18,27], i.e., electrons are in the conduction band and respective holes found in the valence band.

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[1] A quantum dot is a semiconductor heterostructure of nanometric dimensions, which allows the confinement of charge carriers.

[2] QDs density per unit area can range from 10^{11} QDs/cm^2 to low densities as 10^8 QDs/cmˆ2 depending on growth conditions: substrate temperature, growth rate, amount of material deposited among other.

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Therefore in this work we studied how the different distributions or spatial configurations[3] (as shown in Fig. 1) of quantum dots [19] embedded in an optical microcavity and under Von Foerster interaction [30,25,8], affect the statistical properties of the emitted light [7], by calculating the first and second order correlations functions and emission spectra [32] for different configurations, in order to identify and establish characteristics of these systems to advance in their understanding and subsequent manipulation that allows possible technological implementations [2].

This paper is organized as follows: in Section 2, we present the description of the physical system. In Section 3, we introduce the theoretical model proposed for the study of the system at Hamiltonian and dissipative level. In Section 4, we present the results obtained for two configurations of a particular system composed of three interacting quantum dots immersed in an optical microcavity. Specifically, the population dynamics, the emission spectra and the second order correlation functions are shown and discussed. The discussion and conclusions of this work are presented in Section 5.

2. Physical system

The high density exhibiting the typical samples of self-assembled quantum dots [9] allows these interact by sharing their resonance energy by Foerster mechanism because of the proximity between the quantum dots [30,25]. Furthermore, it is also considered the coupling between these interacting quantum dots systems with modes of the cavity in which are embedded [38,35]. A schematic relationship between a typical sample of self assembled quantum dots and different systems that can be generated given the spatial distribution of the sample is presented in Fig. 1(a) and the possible geometric configurations for (n) quantum dots are shown in Fig. 1(b). So in order to investigate the influence that may come to have the different geometric arrangements the following theoretical model is proposed.

3. Theoretical model

3.1. Hamiltonian system

A conventional Hamiltonian model of matter-radiation interaction under the dipolar and rotating wave approximation which includes a variable number of interacting quantum dots (two-level systems) arranged in different geometric configurations where they also interact with a single light mode, is used. A similar treatment can be consulted in Ref. [26]. Thus, the Hamiltonian of the system is:

$$\hat{H} = \hat{H}_C + \hat{H}_{\mathrm{PC}} + \hat{H}_{I_{\mathrm{PC-PC}}} + \hat{H}_{I_{C-\mathrm{PC}}} \tag{1}$$

where $\hat{H}_C$ y $\hat{H}_{\mathrm{PC}}$ are the terms corresponding to the energies of electromagnetic field mode and quantum dots respectively and $\hat{H}_{I_{\mathrm{PC-PC}}}$ and $\hat{H}_{I_{C-\mathrm{PC}}}$ correspond to the interaction energies between quantum dots and the field with the same (radiation–matter interaction) respectively. The general expression for the Hamiltonian of an interacting quantum dots system embedded in an optical microcavity is:

$$\hat{H} = \hbar\omega_C \hat{a}^\dagger\hat{a} + \hbar\omega_X \sum_{i=1}^{N_{\max}} \hat{\sigma}_i^\dagger\hat{\sigma}_i \tag{2}$$

$$+ \hbar g_{N_{\max},1}(\hat{\sigma}_{N_{\max}}^\dagger\hat{\sigma}_1 + \hat{\sigma}_1^\dagger\hat{\sigma}_{N_{\max}}) \tag{3}$$

$$+ \hbar \sum_{i=1}^{N_{\max}-1} g_{i,i+1}(\hat{\sigma}_i^\dagger\hat{\sigma}_{i+1} + \hat{\sigma}_{i+1}^\dagger\hat{\sigma}_i) \tag{4}$$

$$+ \hbar \sum_{i=1}^{N_{\max}} g_i(\hat{a}^\dagger\hat{\sigma}_i + \hat{a}\hat{\sigma}_i^\dagger) \tag{5}$$

where ω_C is the cavity mode frequency, ω_X is the quantum dots frequency or the transition energy between energy levels of the same, $g_{i,j}$ is the Foerster interaction constant, which represents the resonance energy exchange between the quantum dots, g_i is the radiation-matter interaction constant, which describes the dipolar interaction between the dots and light mode, ($\hat{a}^\dagger$ and $\hat{a}$) are the creation and destruction operators of photon and ($\hat{\sigma}^\dagger$ y $\hat{\sigma}$) are the creation and destruction operators of excitons. Moreover, the third term of Eq. (2), $g_{N_{\max},1}(\hat{\sigma}_{N_{\max}}^\dagger\hat{\sigma}_1 + \hat{\sigma}_1^\dagger\hat{\sigma}_{N_{\max}})$ is what defines if the system configuration is opened or closed, that is, if according to the positioning of the considered quantum dots, the interaction chain is closed, allowing to control the first and last point interaction. So, if $g_{N_{\max},1} = 0$, the system is open, while if $g_{N_{\max},1} \neq 0$, the system will be closed. This is shown in Fig. 1(b), by the lines connecting each pair of neighboring quantum dots.

3.2. Dynamics of the system

In Fig. 2 the processes occurring in the system are illustrated through a tower of states. Noting that the Hamiltonian mechanisms

[3] Analytically the spatial distributions of quantum dots samples are taken into account through Foerster interaction between neighboring dots.