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# Polarization switch in an elliptical micropillar – quantum dot system induced by a magnetic field in Faraday configuration

C.A. Jiménez-Orjuela [a,*], H. Vinck-Posada [a], José M. Villas-Bôas [b]

[a] Universidad Nacional de Colombia – Sede Bogotá, Facultad de Ciencias, Departamento de Física, Carrera 45 No. 26-85, C.P. 111321, Bogotá, Colombia
[b] Instituto de Física, Universidade Federal de Uberlândia, 38400-902 Uberlândia, MG, Brazil

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ABSTRACT

In this paper we study the effect of applying a magnetic field on an elliptical microcavity pillar with quantum dots embedded, in the presence of external laser excitation. To obtain the system dynamics we use the matrix density formalism, taking into account realistic parameters and including losses. Our results show that it is possible to use the magnetic field strength to control the polarization of the photons inside the cavity, making our system behave like a photon polarization switch. We also report the best set of parameters where this is possible. Our results also indicate that we can use the polarization of the cavity photons to look into the fine structure of the energy levels of quantum dots.




## 1. Introduction

Semiconductor quantum dots (QDs) embedded in a microcavity have been widely studied during the last decades [1–5], mainly due to its resemblance with atoms, but with physical properties that can be easily manipulated. Interesting phenomena like the Purcell effect [6,7] and the strong coupling regime have been observed [8–13]. These systems have numerous applications, especially in quantum information processing, where QD can be used as qubit, the basis of quantum computers [14–17]. Furthermore, an external magnetic field can modify the spin states of the QD and its energy of confinement, being an excellent tool to control and to investigate its physical properties [18], e.g., a magnetic field applied to a QD embedded inside a cavity has been used to control the cavity occupation and the photon polarization when the system is pumped by a fast laser pulse [19–22]. In addition, when the magnetic field is in the Voigt configuration (in plane) it rises another kind of states known as dark excitons [23,24].

In this paper we consider a self-assembled quantum-dot where the exciton state has a fine structure splitting, presenting two linearly polarized emission lines. The QD is embedded in a elliptical cavity pillar which has two linearly polarized modes strongly coupled with the exciton states according to the selection rules [19]. The reference [25] shows that this system has polarization-dependent strong-coupling regime and that the photoluminescence emission is split into two linearly polarized cavity modes, but its main control parameter is the temperature. While in the reference [26] the polarization dependence of a two coupled QD-cavity is shown in the emission including phonons. In contrast, here we consider an external magnetic field as the control parameter instead the temperature, because the temperature may introduce decoherence and it destroys the quantum properties of the system. The magnetic field **B** in the Faraday configuration mixes and splits the linearly polarized exciton states of the QD due to the Zeeman effect. To understand the effect of the magnetic field, we consider a laser with a certain linear polarization pumping the cavity coherently and then, we solve the master equation to obtain the density matrix. An illustration of our system as well as the coherent and incoherent interactions can be visualized in the Fig. 1.

Once we have the density matrix by solving the master equation, we calculate the expected value of the occupation of each mode of the cavity in several situations. Our results indicate that it is possible to obtain a population of photons in the cavity with orthogonal polarization to the laser one for some values of magnetic field intensity and laser frequency. An analysis of the polarization of the cavity photons also allows us to completely map the exciton states of the QD.

## 2. Model

In our model we will consider only bright exciton states with single occupation, which is valid for low excitation power. We will assume that the QD has an asymmetry, which makes the exciton states to split in two linear polarized states with frequencies $\omega_1$

* Corresponding author.
*E-mail address:* cajimenezo@unal.edu.co (C.A. Jiménez-Orjuela).

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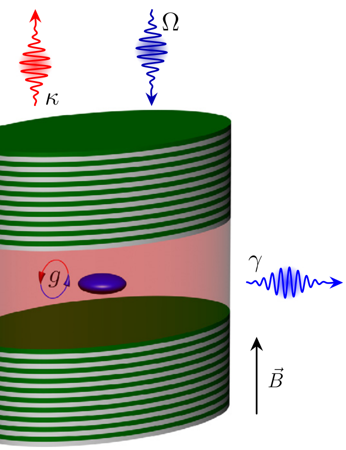


**Fig. 1.** Scheme of the quantum dot-cavity system considered here. A magnetic field $\vec{B}$ parallel to the growth direction is used to switch the photon polarization of the pumped light in an asymmetric cavity. Here $\kappa$ and $\gamma$ are the loss of cavity and decay of the QD respectively and $\Omega$ represent the coherent laser pump.

and $\omega_2$ for $x$ and $y$ polarizations, respectively. With this assumption, the Hamiltonian of the QD can be written as (with $\hbar = 1$)

$$H_{QD} = \omega_1 \sigma_{11} + \omega_2 \sigma_{22} + \frac{\delta_1}{2} \left(\sigma_{12} + \sigma_{21}\right), \tag{1}$$

where $\sigma_{ij} = |i\rangle \langle j|$, with $i, j = 0, 1, 2$, for vacuum (no excitation), exciton with $x$ and $y$-polarization, respectively. Here we assume an excitonic fine-structure splitting $\delta_1 = \omega_2 - \omega_1 = 100$ μeV. A magnetic field applied in the growth direction will mix and diamagnetically shift the two exciton states, adding the following term to the QD Hamiltonian

$$H_{\text{mag}} = \imath\beta(\sigma_{12} - \sigma_{21}) + \alpha B^2(\sigma_{11} + \sigma_{22}), \tag{2}$$

where $\beta = \mu_B B(g_{ez} + g_{hz})/2$, with $\mu_B = 57.9$ μeV/T being the Bohr magneton, $g_{ez}$ and $g_{hz}$ are the electron and hole effective $g$-factor in the $z$ directions. In the last term, $\alpha$ is the diamagnetic shift coefficient [13], which we assumed to be identical for both exciton states. Here we use $g_{hz} = -2.2$ and $g_{ez} = -0.8$ and $\alpha = 20$ μeV/T$^2$, which are typical values for InAs/GaAs QD[23].

As for the cavity part of the Hamiltonian, we consider an elliptical micro pillar cavity with two orthogonal photonic modes with frequencies $\omega_x$ and $\omega_y$. The modes are also linear polarized $(x, y)$ and non-degenerated because of the asymmetry of the micro pillar cavity [19]. We assume the mode splitting $\Delta = \omega_y - \omega_x = 200$ μeV and fix $\omega_x = 1$ eV. The cavity modes interact with excitons of the same polarization, therefore, the cavity Hamiltonian can be written as

$$\begin{aligned} H_{\text{cav}} &= \omega_x a_x^\dagger a_x + g_x(a_x^\dagger \sigma_{01} + a_x \sigma_{10}) \\ &+ \omega_y a_y^\dagger a_y + g_y(a_y^\dagger \sigma_{02} + a_y \sigma_{20}), \end{aligned} \tag{3}$$

where $a_x^\dagger$ ($a_y^\dagger$) is the creation operator for photons with $x$ ($y$)-polarization inside the cavity, and $g_x$ ($g_y$) is the light-matter coupling strength between photons and excitons. Here we assume that such couplings rates are independent of the polarization and have values $g_x = g_y = 100$ μeV.

The cavity modes can be externally pumped with a laser field, which can be modeled by

$$H_{\text{pump}} = \Omega_x(t)(a_x e^{\imath\omega_L t} + a_x^\dagger e^{-\imath\omega_L t}). \tag{4}$$

The system may be pumping to exciton instead to cavity, however, we prefer to use a laser field directly to cavity because we are interested in light input/output processes, so we want to follow the polarization of light output with respect to the polarization of light input. Here $\omega_L$ is the laser frequency and $\Omega_x(t)$ is the pumping intensities to the cavity modes, which is constant for a continuous wave (cw) laser or has a time dependence in the case of a pulsed laser. For this last case we use pulses with Gaussian shape of the form: $\Omega_x(t) = \Theta_x \exp\left[-(t - t_c)^2/2\tau^2\right]$, where $\Theta_x$ is the energy amplitude of the pulse, $t_c$ is the time of the center of the pulse and $\tau$ is the Gaussian RMS width.

The full Hamiltonian of our system can then be written as

$$H = H_{QD} + H_{\text{mag}} + H_{\text{cav}} + H_{\text{pump}}. \tag{5}$$

To obtain the dynamics of this system we solve numerically the master equation in the Lindblad form with the Markov approximation:

$$\begin{aligned} \frac{d\rho}{dt} &= -\imath[H, \rho] + \kappa_x \mathcal{D}[a_x] + \kappa_y \mathcal{D}[a_y] \\ &+ \gamma_1 \mathcal{D}[\sigma_{01}] + \gamma_2 \mathcal{D}[\sigma_{02}] \end{aligned} \tag{6}$$

where $\mathcal{D}[L] = L\rho L^\dagger - \frac{1}{2}(L^\dagger L\rho + \rho L^\dagger L)$ is the Lindblad superoperator, which contains the incoherent and dissipative terms influencing the system. Here $\kappa_{x,y}$ are the cavity loss rate and $\gamma_{1,2}$ are the exciton decay rate for $x, y$-polarization. We again assume that these parameters are independent of the polarization, being $\kappa_x = \kappa_y = 20$ μeV and $\gamma_1 = \gamma_2 = 2$ μeV. Our result does not vary for a $\kappa$ factor in the range ($\kappa \leq 60$ μeV), which is a realistic value for a cavity factor $Q \sim 20000$, and in the optical regime (where our work is) $\omega \sim 1$ eV. Our control parameters are the magnetic field intensity $B$ and the laser detuning with the cavity mode, $\delta_L = \omega_L - \omega_c$, where $\omega_c = (\omega_x + \omega_y)/2$. To numerically solve the density matrix we expand the system state in the basis $\{|nx, ny, s\rangle\}$, where $|nx\rangle$ and $|ny\rangle$ is the Fock basis for the $x$ and $y$-polarization mode of the cavity, respectively, and $|s\rangle$ is the QD exciton states as described before.

## 3. Results

The polarization of emitted light has shown having a dependence with the temperature and detuning, see reference [26]. Here, we are interested in controlling the cavity photon polarization using a magnetic field. Once we obtain the density matrix, we can compute the mean value of any operator using $\langle O \rangle = \text{Tr}[O\rho]$. Here we are particularly interested in $\langle a_x^\dagger a_x \rangle$ and $\langle a_y^\dagger a_y \rangle$, the photon mean number for each cavity mode polarization.

Firstly, we consider a cw laser with $x$-polarization and that the QD excitons are initially detuned from the cavity mode $\omega_c - \omega_0 = 0.5$ meV, where $\omega_0 = (\omega_1 + \omega_2)/2$. We then vary the laser frequency and the applied magnetic field intensity, monitoring the cavity occupation of each polarization in the steady state. The result is shown in Fig. 2.

Here we used a very low power excitation, $\Omega_x = 10$ μeV. As we can see in the upper panel of the Fig. 2, $\langle a_x^\dagger a_x \rangle$, the cavity mode with the same polarization of the laser is populated when the laser is at resonance with the cavity mode and it is mostly independent of the magnetic field, except in regions with avoided crossing between the QD energy levels and the cavity mode with $x$-polarization, which happens around 3 T and 7 T. The effect of the magnetic field is to bring the QD energy levels in resonance with cavity mode and mix the $x$ and $y$ excitons polarizations. In the lower panel of Fig. 2 we show the cavity occupation for $y$-polarization, $\langle a_y^\dagger a_y \rangle$. This occupation is lower than the $x$-polarization one and presents a triple anticrossing. Here we can see when one of the exciton states anticrosses with the $x$-polarization cavity mode (around 3 T) and with the $y$-polarization mode (around 3.75 T). Similar behavior happens around 7 T and 8 T when the second exciton state is at resonance