Dynamical Model of Optical Polarisation Rotation in a Charged Quantum Dot - Micropillar System

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***Abstract*—We employ a quantum master equations approach based on a vectorial Maxwell-pseudospin model to describe the polarisation dynamics of a negatively charged quantum dot embedded in a micropillar cavity upon an ultrashort optical excitation. We demonstrate numerically a giant optical polarisation rotation ($\sim \pm\pi/2$) of a resonant circularly polarised pulse in realistic dot-cavity geometries. The model allows for optimisation of the polarisation rotation angle for realisation of spin-photon entanglement and ultrafast polarisation switching on a chip.**

***Index Terms*—trion, cavity-dot system, polarisation rotation**

I. Introduction

Realisation of a deterministic spin-photon entanglement in semiconductor quantum dots (QDs) is one of the major goals of integrated quantum photonics. In general, there are two possible ways of realising a quantum superposition of states: through controlled rotations of either 1) the material spin qubit or 2) the photon polarisation state representing the qubit. Coupling a stationary spin qubit to an optical cavity enhances the efficiency of spin-photon interaction. Recently, a macroscopic Kerr rotation of photon polarisation ($\sim 6^\circ$) has been observed in both the strong- [1] and weak-coupling [2] regimes in a charged QD-micropillar.

In this work, we develop a dynamical model and investigate numerically realistic micropillar cavity-dot geometries. We show that a resonant coherent interaction of an ultrashort circularly polarised pulse with the trion transition results in a giant rotation angle of π in the weak-coupling regime. Large rotation angles are highly desirable for fabrication of phase gates for optical quantum computing and enable using charged QD-cavities as ultrafast polarisation switches on a chip.

II. Theoretical Model

We consider a negatively charged InGaAs QD embedded in a AlAs/AGaAs micropillar cavity Fig. 1(a). An equivalent four-level scheme of the ground trion singlet transition and the relevant spin relaxation processes is shown in Fig. 1(b). The dynamical evolution of an open 4-level quantum system under a time-dependent perturbation is described by a master pseudospin equation for the real state vector, S_j [3], [4]:

$$\frac{\partial S_j}{\partial t} = \begin{cases} f_{jkl}\Gamma_k S_l + \frac{1}{2}Tr\left(\hat{\sigma}.\hat{\lambda}_j\right) - \frac{1}{T_j}\left(S_j - S_{je}\right), & j = 1,2,..,12 \\ f_{jkl}\Gamma_k S_l + \frac{1}{2}Tr\left(\hat{\sigma}.\hat{\lambda}_j\right), & j = 13,14,15, \end{cases} \tag{1}$$

where Γ_k – torque vector, $\widehat{\lambda}_j$ –generators of $SU(4)$ Lie group algebra, f – fully-antisymmetric tensor of the structure constants; $\hat{\sigma}$ – population relaxation; S_{je} – equilibrium coherence vector, and T_j – phenomenological decay times towards S_{je}.

We solve self-consistently the quantum evolution equations Eqs. (1) and the vector Maxwell equations for a resonant circularly polarised optical pulse interacting with an ensemble of four-level systems (charged QDs) with density N_d:

$$\begin{aligned} \frac{\partial H_x(z,t)}{\partial t} &= \frac{1}{\mu}\frac{\partial E_y(z,t)}{\partial z} \\ \frac{\partial H_y(z,t)}{\partial t} &= -\frac{1}{\mu}\frac{\partial E_x(z,t)}{\partial z} \\ \frac{\partial E_x(z,t)}{\partial t} &= -\frac{1}{\varepsilon}\frac{\partial H_y(z,t)}{\partial z} - \frac{1}{\varepsilon}\frac{\partial P_x(z,t)}{\partial t} \\ \frac{\partial E_y(z,t)}{\partial t} &= \frac{1}{\varepsilon}\frac{\partial H_x(z,t)}{\partial z} - \frac{1}{\varepsilon}\frac{\partial P_y(z,t)}{\partial t}. \end{aligned} \tag{2}$$

where the polarisation components are given by: $P_x = -\wp N_d S_1$;$P_y = -\wp N_d S_7$. $\wp = \langle 1|e\mathbf{r}|2\rangle = \langle 3|e\mathbf{r}|4\rangle$ is the dipole matrix element. The optical rotation angle of a transmitted through the cavity pulse is calculated from the phase shift induced by the resonant absorption of the QD layer with thickness $l = z_2 - z_1$. The resonant phase shift is given by $\Delta\varphi_{x,y} = \beta_{x,y} l$, where $\beta_{x,y} = \frac{1}{l}\arctan\left(\frac{\mathrm{Im}(z_{x,y})}{\mathrm{Re}(z_{x,y})}\right)$ and $z_{x,y} = \frac{E_{x,y}(z_2,\omega)}{E_{x,y}(z_1,\omega)} = e^{ik_{cx,y}l}$ is the complex propagation factor, given by Fourier transform of the time traces of the E_x and E_y sampled at the end points of the QD layer (Fig. 2(a)).

E_{trion} **[eV]**	λ_0 **[nm]**	T_p **[fs]**	E_0 $[Vm^{-1}]$	$\wp$ **[e.nm]**	N_d $[m^{-3}]$	**Relaxation times [ps]**				
						Γ	γ_1	γ_2	γ_3	Γ_τ
1.388	894	100	1.44×10^8	0.57	3.18×10^{24}	820 [2]	500 [5]	450 [7]	170 [6]	340

III. Numerical method and results

Eqs. (1-2) are solved directly in the time domain by the Finite-Difference Time-Domain (FDTD) method. The resonant Gaussian circularly polarised pulse, is given by:

$$\sigma^{\pm}\begin{cases} E_x(z=L,t) = E_0 exp\left[-(t-t_0)^2/t_d^2\right]\cos(\omega_o t) \\ E_y(z=L,t) = \pm E_0 exp\left[-(t-t_0)^2/t_d^2\right]\sin(\omega_o t) \end{cases} \tag{3}$$

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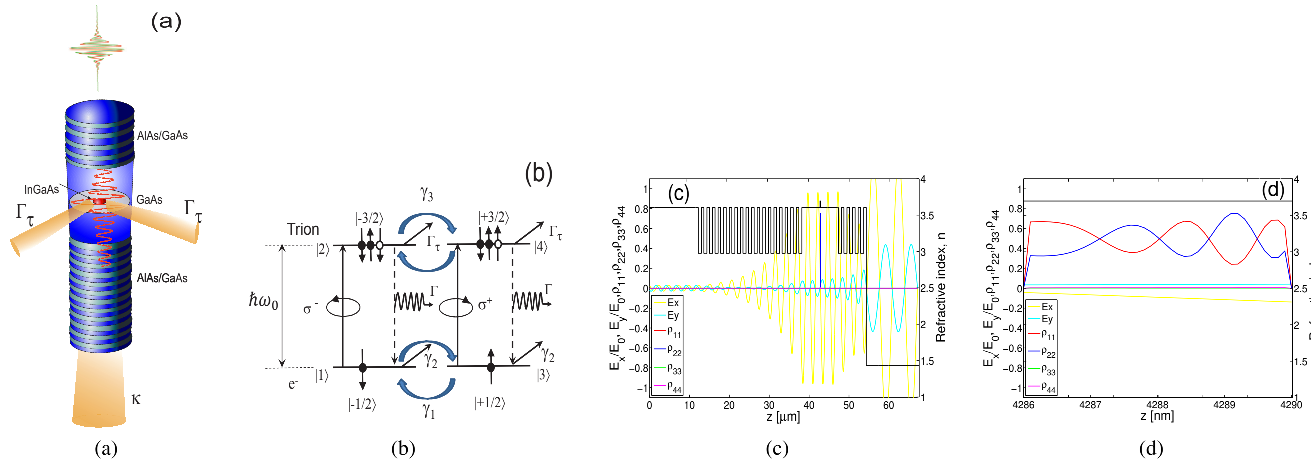

Fig. 1. (a) Sketch of a charged QD-micropillar structure; κ - cavity loss, Γ_τ - trion decay rate to non-cavity modes. The micropillar cavity is pumped from the top (through an optical fibre) by an ultrashort circularly polarised pulse; (b) Energy-level diagram of the negative trion ground singlet transition driven resonantly by either left- (σ^-) or right-(σ^+) circularly polarised light. Electron (γ_1) / hole (γ_3): spin flip relaxation rates; Γ: spontaneous emission rate; γ_2, Γ_τ: spin decoherence rates. (c) Refractive-index profile (black line) of the micropillar with embedded QD [2], and a snapshot of the E-field components (yellow and cyan curves) and level populations (red, blue, green and magenta) at t=3.33 ps. (c) Zoom-in on (b) of the QD layer.

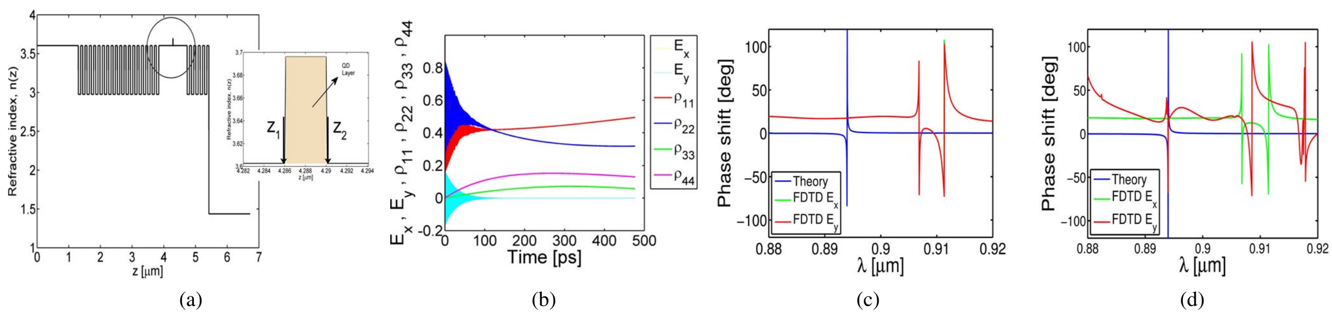

Fig. 2. (a) Refractive index profile of the micropillar from [2]; inset: zoom-in of the region around the QD layer; z_1 and z_2 denote the left and right end points of the QD layer; (b) Time evolution of the E-field components of a σ^- pulse and level populations at z_2 for a spin-down initial state; ρ_{22} (blue curve) proportional to experimentally detected TRPL; (c) Phase shift (in degrees) of the E_x and E_y pulse components of a σ^- - pulse. Blue curve: stationary solution of the density-matrix equations for a two-level system (no cavity), (d) Phase shift of the E-field components of a linearly x-polarised pulse.

where $\pm$ corresponds to right(left) circularly polarised pulse with amplitude E_0, or $E_y = 0$ for $x-$ linearly polarised pulse. The model parameters are summarised in Table I.

Consider initial spin-down population prepared entirely in ground level $|1\rangle$ e.g. by e.g. optical pumping [8]. The temporal dynamics of the E-field components of a σ^- pulse and populations of all levels is calculated at the end points, z_1 and z_2, of the QD layer (see Fig.2(a,b)). We numerically demonstrate a giant phase shift of $\pm\pi/2$, induced by the single spin confined in the QD in a range of realistic micropillar cavities (Fig.2(c)). We calculate the cavity transmission spectrum and the cavity loss, $\kappa = 1.25$ ps$^{-1} \gg \Omega_R \sim 125$ ps^{-1} – weak coupling regime. By contrast, when the trion transition is driven by a resonant x-linearly polarised pulse, we show that the orthogonal (y) E-field pulse component (initially set to zero) is building up in time, thereby leading to a polarisation rotation. The time delay in the E_y amplitude build-up results in a red shift in the phase shift spectrum with respect to the one for the E_x (Fig.2(d)). This displacement effectively leads to destructive interference and significant reduction of the optical rotation angle. In summary, we demonstrate numerically a giant $\sim \pm\pi/2$ optical rotation for a circularly polarised ultrashort pulse, which exceeds by an order of magnitude the Kerr polarisation rotation angles obtained by cw linearly polarised excitations. Our method allows to design and test cavity-dot structures with maximised photon polarisation rotation angles and thus prepare high-fidelity photon qubit states.

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