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 within an ultrashort optical excitation. We demonstrate numerically a giant optical polarisation rotation (∼±π/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—tron, 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 (∼6°) 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/AgAs 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]:

\[
\frac{dS_j}{dt} = \left\{ \begin{array}{ll}
\sum_{k} \Gamma_k \langle \hat{S}_j \rangle \left( \hat{S}_k - \frac{1}{2} \hat{S}_j \right), & j = 1, 2, ..., 12 \\
\sum_{k} \Gamma_k \langle \hat{S}_j \rangle \left( \hat{S}_k - \frac{1}{2} \hat{S}_j \right), & j = 13, 14, 15,
\end{array} \right.
\]

where \(\Gamma_k\) – torque vector, \(\hat{\lambda}_j\) – generators of \(SU(4)\) Lie group algebra, \(f\) – fully-antisymmetric tensor of the structure constants; \(\sigma\) – 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 pulse interacting with an ensemble of four-level systems (charged QDs) with density \(N_d\):

\[
\begin{align*}
\frac{\partial H_x(z,t)}{\partial t} &= \frac{1}{\mu} \frac{\partial E_y(z,t)}{\partial z} \\
\frac{\partial H_y(z,t)}{\partial t} &= -\frac{1}{\mu} \frac{\partial E_x(z,t)}{\partial z} \\
\frac{\partial E_x(z,t)}{\partial t} &= \frac{1}{\varepsilon} \frac{\partial H_y(z,t)}{\partial z} - \frac{1}{\varepsilon} \frac{\partial P_d(z,t)}{\partial t} \\
\frac{\partial E_y(z,t)}{\partial t} &= -\frac{1}{\varepsilon} \frac{\partial H_x(z,t)}{\partial z} - \frac{1}{\varepsilon} \frac{\partial P_d(z,t)}{\partial t},
\end{align*}
\]

where the polarisation components are given by: \(P_x = -\varphi N_d S_{11} P_y = -\varphi N_d S_{77}\). \(\varphi = \langle 1 \mid e \rangle = \langle 3 \mid e \rangle\) 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 \(\Delta \varphi_{x,y} = \beta_{x,y}\), where \(\beta_{x,y} = \frac{1}{\hbar} \arctan \left( \frac{\Im \left( z_{x,y} \right)}{\Re \left( z_{x,y} \right)} \right)\) and \(z_{x,y} = \frac{E_{x,y}(z_2,\omega)}{E_{x,y}(z_2,\omega)} = e^{i k_{x,y} l}\) 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)).

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:

\[
\sigma_{\pm} = \begin{cases} 
E_x(z = L, t) = E_0 e^{i \omega t} \left[ 1 - \left( t - t_0 \right)^2 / T_d^2 \right] \cos(\omega t) \\
E_y(z = L, t) = \pm E_0 e^{i \omega t} \left[ 1 - \left( t - t_0 \right)^2 / T_d^2 \right] \sin(\omega t)
\end{cases}
\]

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where ± 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) e.g. by e.g. optical pumping [8]. The temporal dynamics of the E-field components of a $\sigma^-$ 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.

REFERENCES