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All-optical Coherent Control of Spin Dynamics in Semiconductor Quantum Dots

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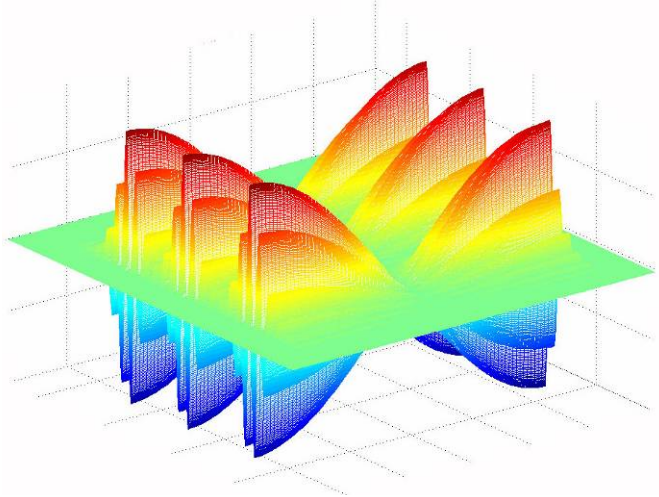


Electron spin in a single Quantum Dot

attractive qubit candidate for physical implementation of quantum computation

- Severe limitation for quantum computing with excitons/biexcitons in QDs : coupling to lattice phonons and non-scalability

Long spin coherence and spin relaxation times ensuring long-lived quantum state:

- Long spin relaxation lifetimes T_1 ~ ms range (Elzerman et al. Nature, 430,431 (2004); Kroutvar et al., Nature 432,81 (2004))
- Long electron spin coherence times T_2 measured in bulk SCs exceeding 100 ns (Kikkawa and Awschalom, Science 287, 473 (2000))
- Long electron spin coherence times $T_2 \sim 2T_1$ expected in QDs
- Extended spin coherence time T_2 in the high-intensity excitation regime when Rabi oscillations occur (Petta et al. Science 309, 2180 (2005))

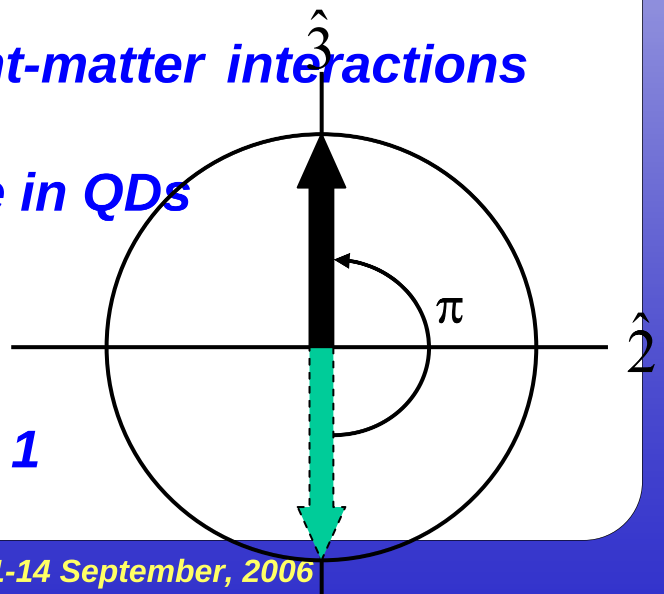
- Optical spin orientation: conversion of quantum information from light to spin and vice versa
- The ability to faithfully transmit 'flying qubits' between distant locations
- Scalable model (to $\geq$100 coupled qubits)

Quantum coherent optical control of electron spin in nanostructures

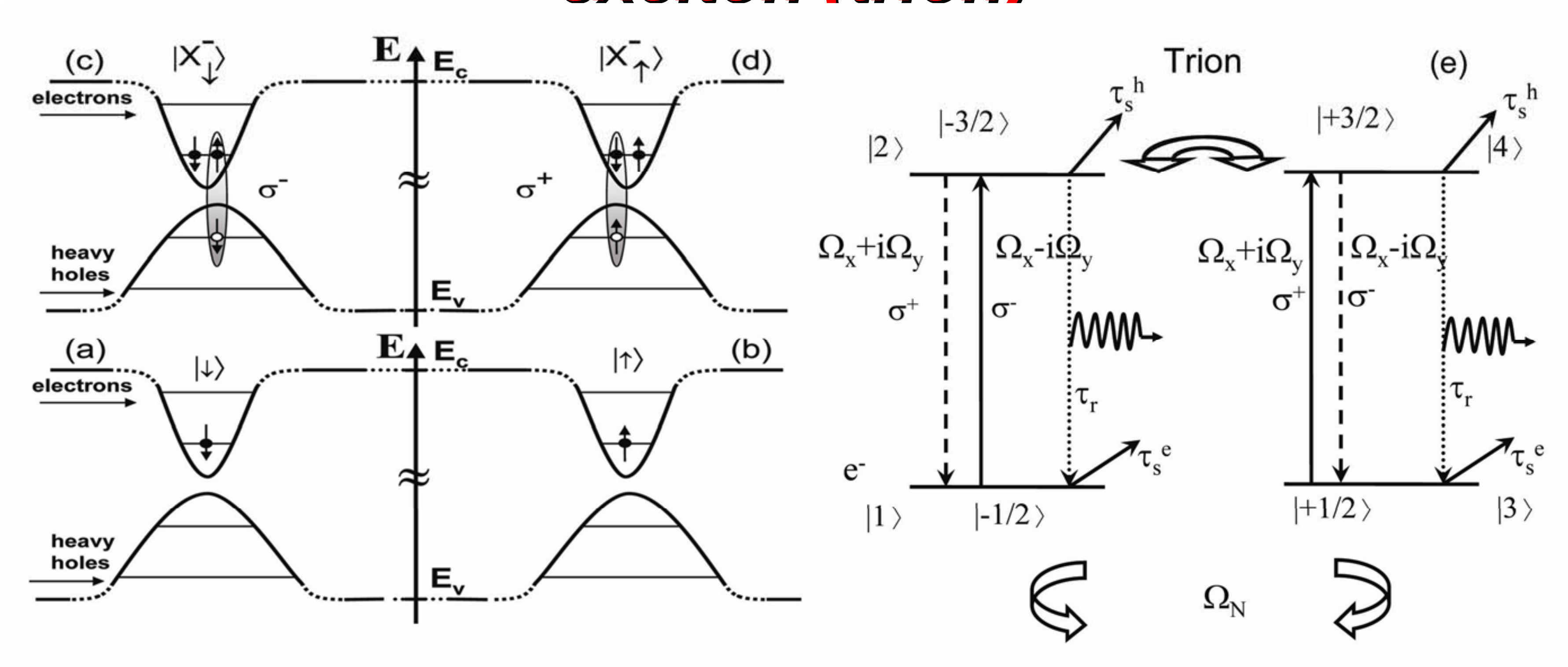
- Predictable manipulation of the quantum dynamics of the system on a time scale shorter than typical dephasing times
- Necessary condition for quantum coherence: use of ultrashort optical pulses
- Recent progress in coherent preparation and detection of single electron spin states (Hartmann et al. PRL 84, 5648 (2000); Warburton et al. Nature 405, 926 (2000); Tischler et al. PRB 66, 081310 (2002); Rugar et al. Nature 430, 329 (2004); Xiao et al. ibid. 430, 435 (2004))

Exploiting the resonant optical nonlinearities of the QDs in the high-intensity excitation regime:

- Optical Rabi oscillations: coherent nonlinear light-matter interactions in discrete-level systems
- Population flopping over many periods is possible in QDs
  - systems with long coherence lifetimes
  - large dipole moments
- A Rabi flop corresponds to one-qubit rotation where the bit is rotated through π (i.e. from state $0 \rightarrow 1$ and vice versa)



Energy-level diagram of a negatively charged exciton (trion)



Similarities between QD and atomic systems:

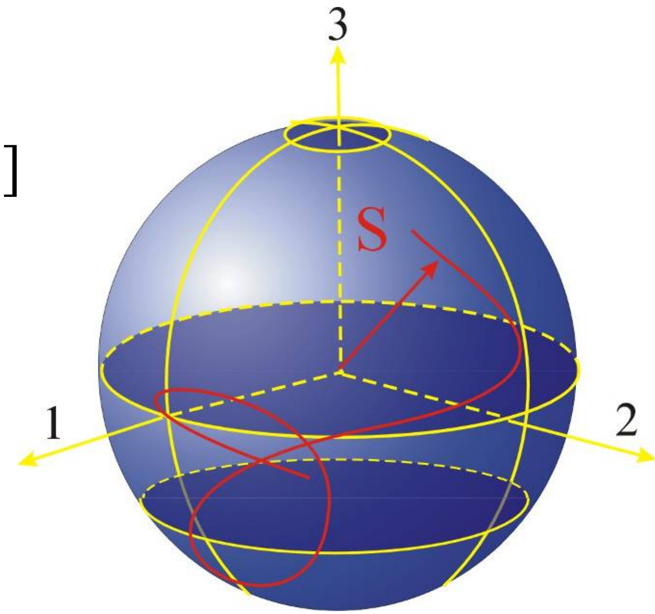
- ***Discrete-level electronic structure (3D carrier quantum confinement)***
- ***Fulfil DiVincenzo criteria: a few-energy level system, well isolated spectrally and insensitive to external perturbations (due to localised eigenstates)***

Model of the coherent spin dynamics Theoretical fundamentals

Dynamical evolution of an N-level quantum system:

Liouville equation (Schrödinger picture):

$$i\hbar \frac{\partial \hat{\rho}}{\partial t} = [\hat{H}, \hat{\rho}]$$



Pseudospin equation for the real state vector $S = (S_1, S_2, \ldots, S_{N^2-1})$ (Heisenberg picture)

(Hioe and Eberly, PRL, 47, 838,1981)

$$\frac{\partial S_i}{\partial t} = f_{ijk}\gamma_j S_k \qquad i, j, k = 1, \ldots, N^2 - 1$$

Using Gell-Mann's λ-generators of the SU(N) Lie algebra:

Pseudospin (coherence) vector

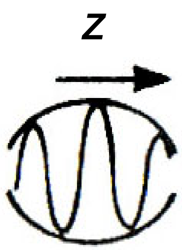
$$S_j(t) = Tr\left(\hat{\rho}(t)\hat{\lambda}_j\right)$$

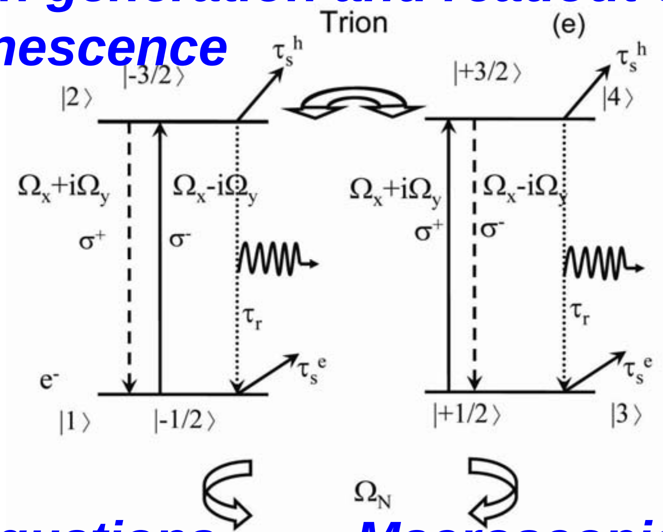
torque vector

$$\gamma_j(t) = \frac{1}{\hbar} Tr\left(\hat{H}(t)\hat{\lambda}_j\right)$$

Coherent Maxwell-pseudospin equations for a four-level system

Optical spin generation and readout of the electron spin state via polarised photoluminescence





$$\hat{H}=\hbar\begin{pmatrix} 0 & -\frac{1}{2}(\Omega_x-i\Omega_y) & 0 & 0 \\ -\frac{1}{2}(\Omega_x+i\Omega_y) & \omega_0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{2}(\Omega_x+i\Omega_y) \\ 0 & 0 & -\frac{1}{2}(\Omega_x-i\Omega_y) & \omega_0 \end{pmatrix}$$

$$\Omega_x=\frac{\wp}{\hbar}E_x; \quad \Omega_y=\frac{\wp}{\hbar}E_y$$

Maxwell's equations

$$\begin{cases} \dfrac{\partial \mathbf{H}}{\partial t}=-\dfrac{1}{\mu}\nabla\times\mathbf{E} \\ \dfrac{\partial \mathbf{E}}{\partial t}=\dfrac{1}{\varepsilon}\nabla\times\mathbf{H}-\dfrac{1}{\varepsilon}\dfrac{\partial \mathbf{P}}{\partial t} \end{cases}$$

Macroscopic polarisation

$$P_x=-\wp N_a(S_1+S_6)$$
$$P_y=-\wp N_a(S_7-S_{12})$$
$$\sigma=diag(1/T_1,1/T_2,\ldots,1/T_{15})$$

Pseudospin equations

$$\frac{\partial \mathbf{S}}{\partial t}=M\,\mathbf{S}-\sigma(\mathbf{S}-\mathbf{S}_E)$$

$$M=\begin{pmatrix} \underline{P}_{6\times6} & \underline{Q}_{6\times6} & \underline{R}_{6\times3} \\ -\underline{Q}^T{}_{6\times6} & \underline{P}_{6\times6} & \underline{S}_{6\times3} \\ -\underline{R}^T{}_{3\times6} & -\underline{S}^T_{3\times6} & \underline{0}_{3\times3} \end{pmatrix}$$

Source optical field

$$\sigma^-\begin{cases} E_x(z=0,t)=E_o sech(10\Gamma)\cos(\omega_o t) \\ E_y(z=0,t)=-E_0 sech(10\Gamma)\sin(\omega_o t) \end{cases}$$

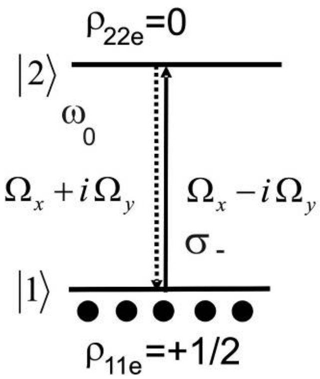
$$\sigma^+\begin{cases} E_x(z=0,t)=E_o sech(10\Gamma)\cos(\omega_o t) \\ E_y(z=0,t)=E_0 sech(10\Gamma)\sin(\omega_o t) \end{cases}$$

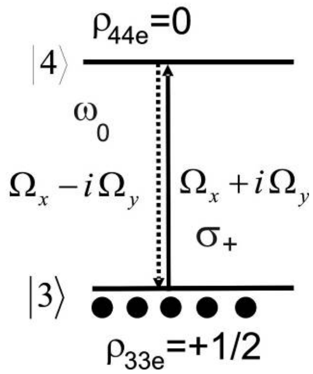
$$\Gamma=[t-(T_p/2)]/(T_p/2)$$

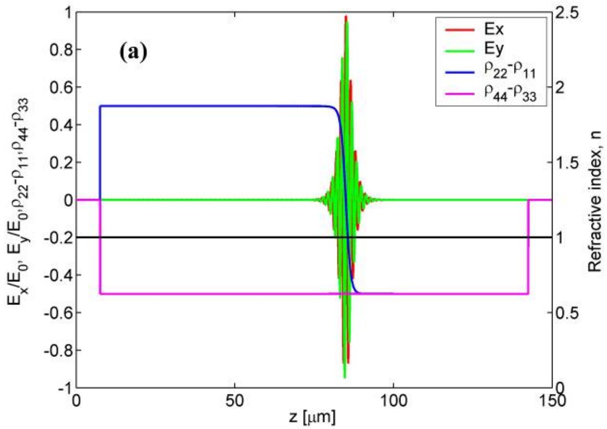
Selective spin state excitation

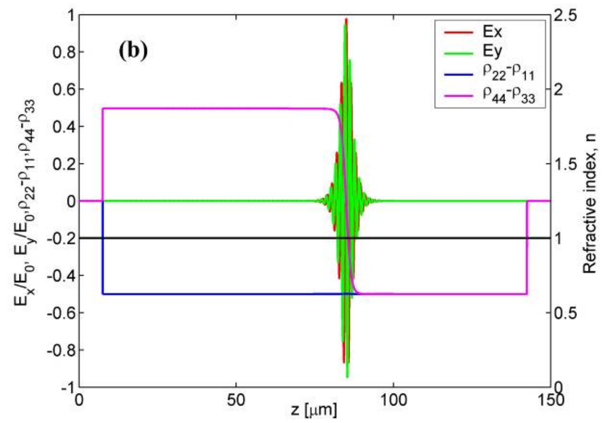
π-pulse E_0=2.1093×10^9 V.m^{-1}, T_p=100 fs, λ=1.5 µm

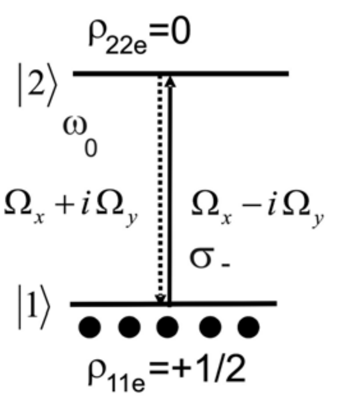
σ^- (π-pulse) **σ^+(π-pulse)**

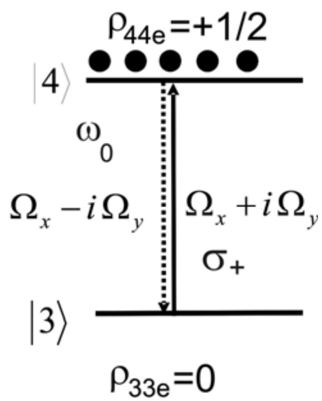


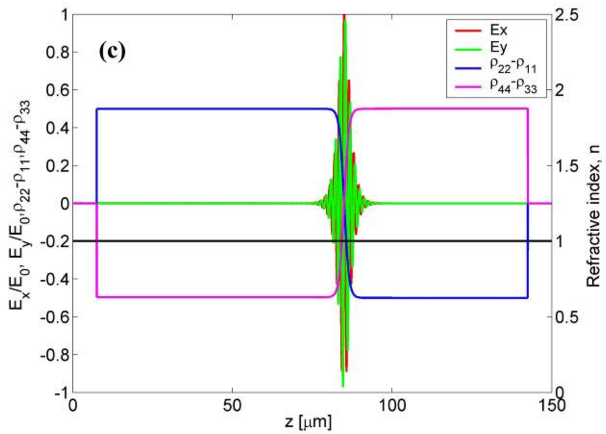


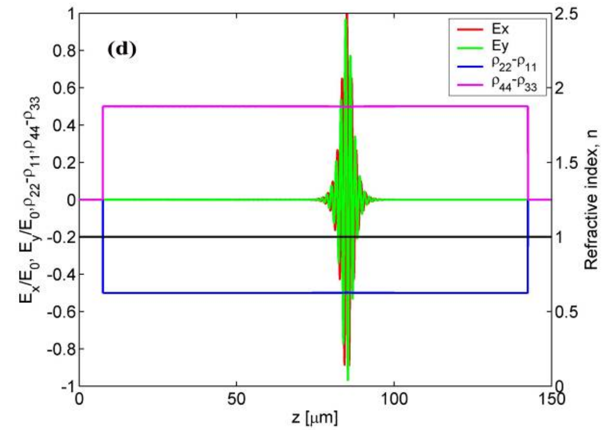








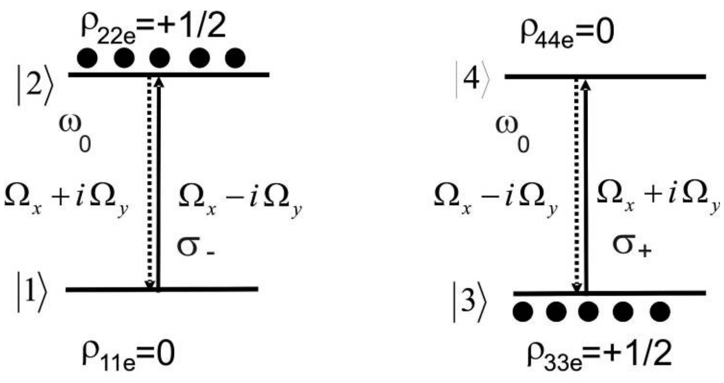


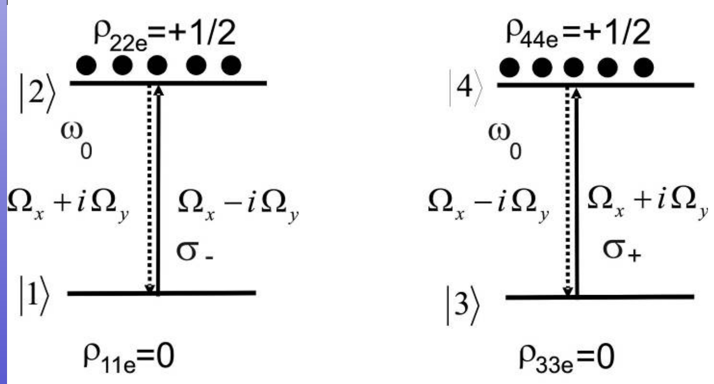


T_1=T_6=T_7=T_{12}=100 ps, T_{13}=T_{14}=T_{15}=100 ps

Selective spin state excitation

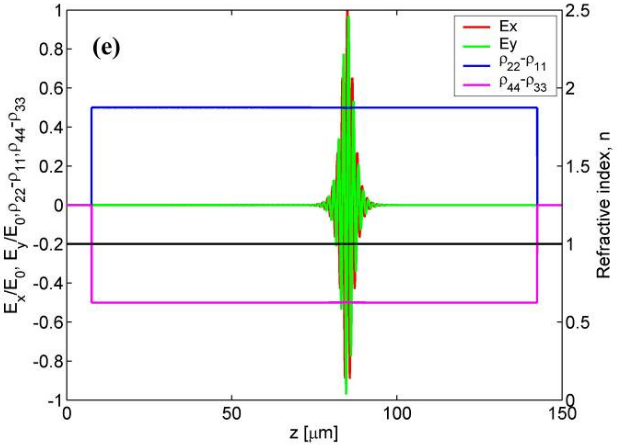
π-pulse E_0=2.1093×10^9 V.m^{-1}, T_p=100 fs, λ=1.5 μm

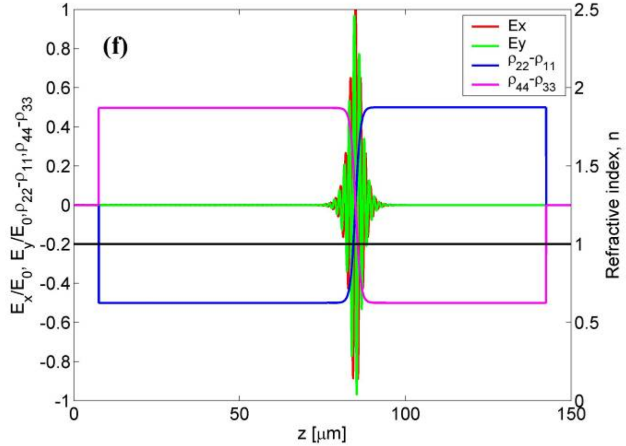


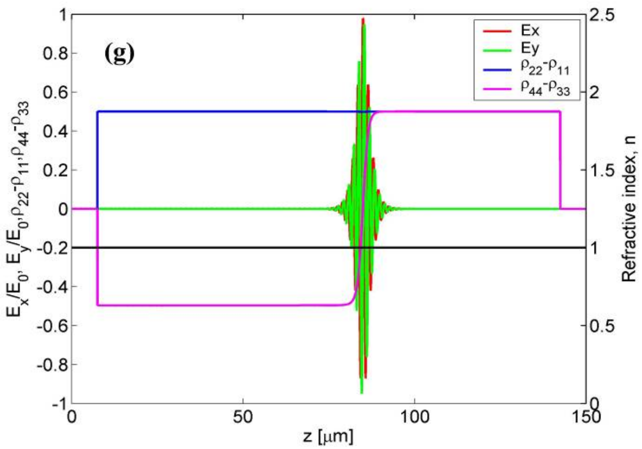


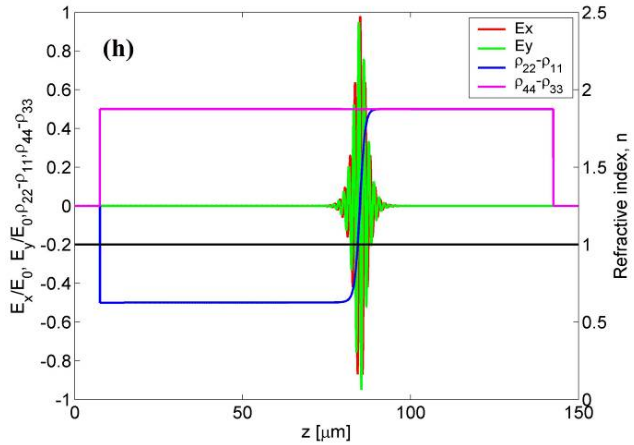
σ^- (π-pulse)

σ^+(π-pulse)



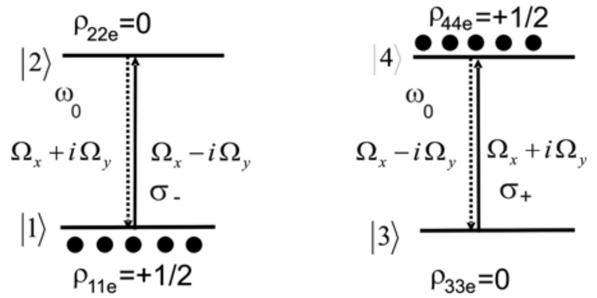




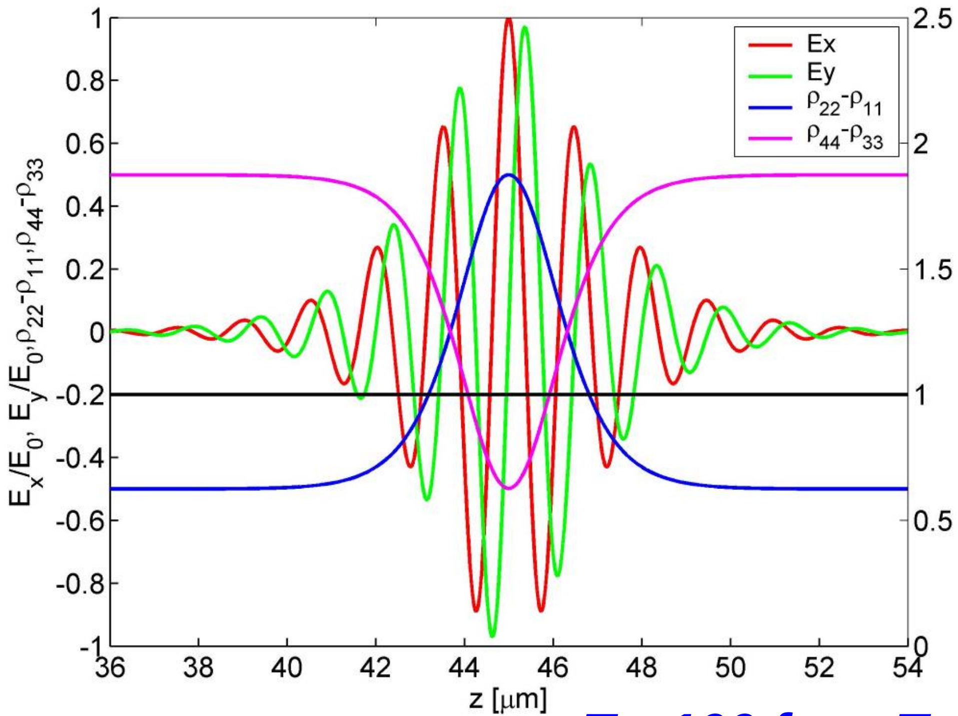


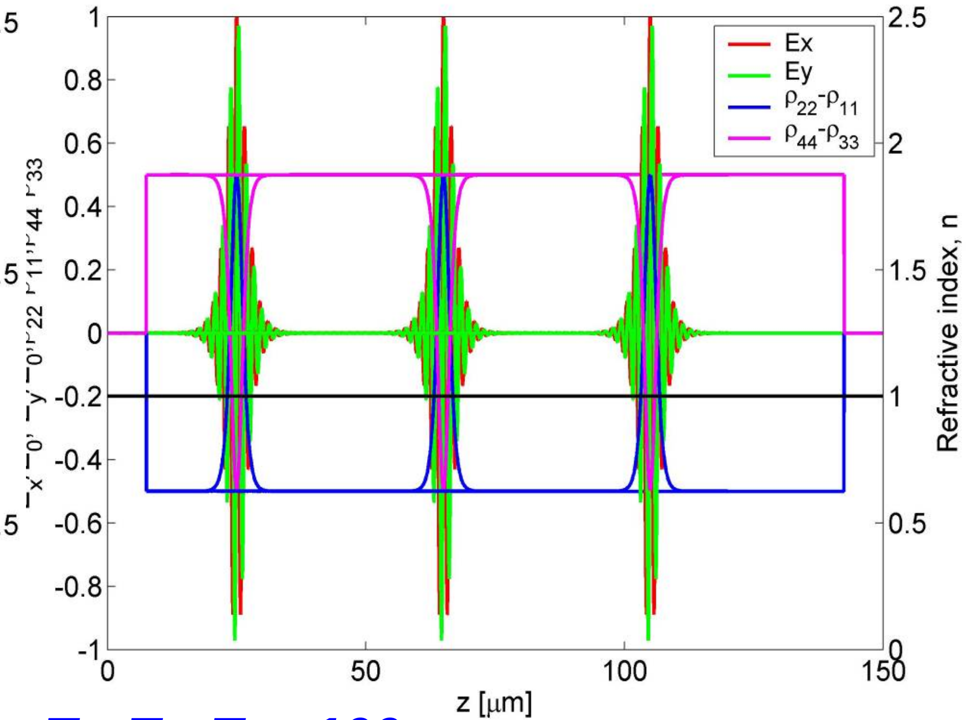
$T_1=T_6=T_7=T_{12}$=100 ps, $T_{13}=T_{14}=T_{15}$=100 ps

Self-Induced Transparency in a degenerate four-level system



2π-pulse E_0=4.2186×10^9 V.m^{-1}

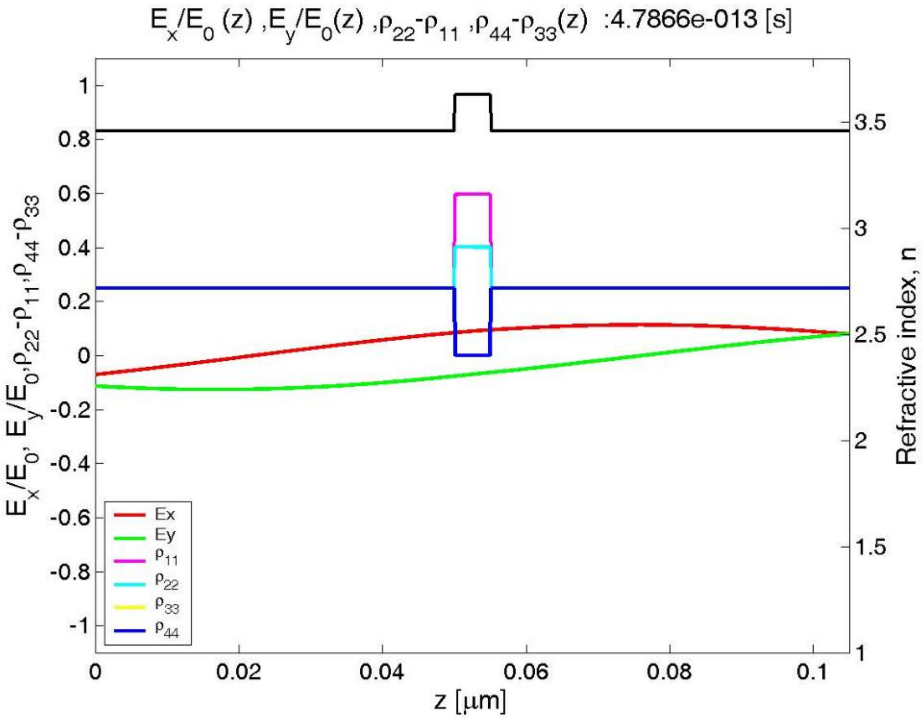


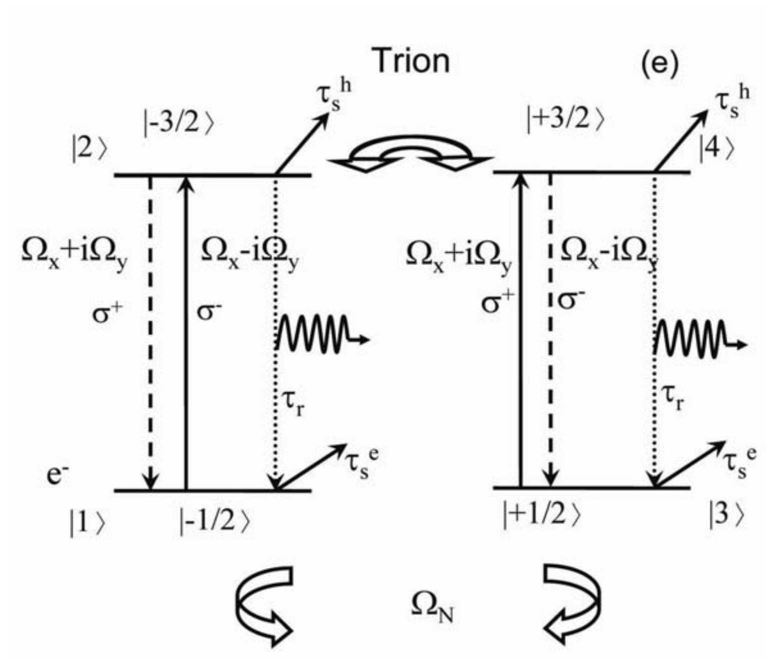


T_p=100 fs <<T_1=T_6=T_7=T_{12}=100 ps; T_{13}=T_{14}=T_{15}=100 ps

Trion optically-induced coherent spin dynamics

GaAs/$Al_{0.3}Ga_{0.7}$As self-assembled modulation-doped QD





λ =787 nm, T_p=1 ps, $T_2=T_4=T_8=T_{10}=\infty$

$T_3=T_9=\tau_s^e$ = 0.5 ns hyperfine interaction **(Shabaev et al., PRB 68, 201305, 2003; Merkulov et al., PRB 65, 205309, 2002)**

$T_5=T_{11}=\tau_s^h \sim$ 1 µs phonon-assisted process **(Takagahara et al., PRB 62, 16840, 2000)**

$T_1=T_6=T_7=T_{12}$=0.5 ns trion spin dephasing time (**Economou et al., PRB 71, 195327, 2005)**

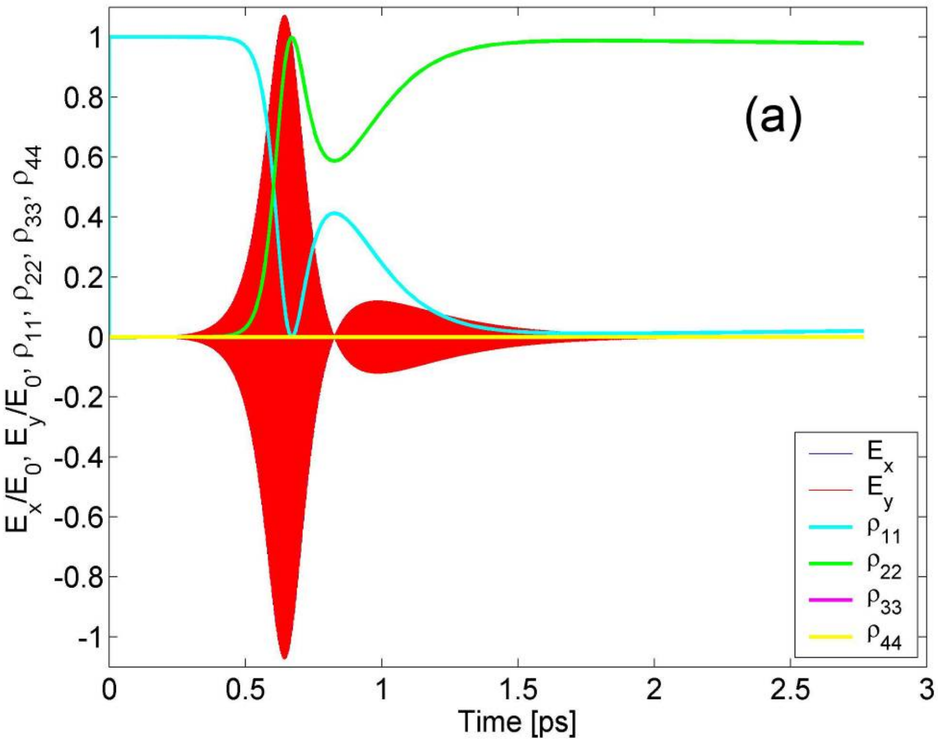
$T_{13}=T_{14}=T_{15}=\tau_r$=100 ps trion radiative decay time (recombination time) **(Shabaev et al. 2003, Economou et al. 2005, Greilich et al. , PRL 96, 227401, 2006)**

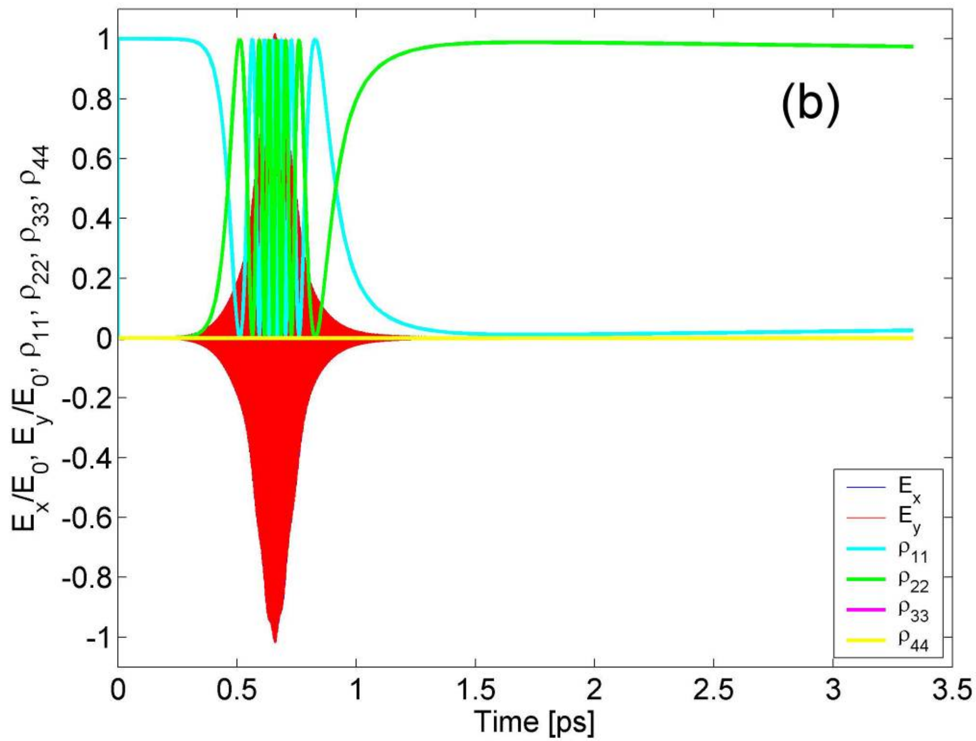
Trion optically-induced coherent spin dynamics

σ^{-}-pulse T_p=1 ps, λ=787 nm,
ω_0=2.39 $\times$ 10^{15} rad.s^{-1}

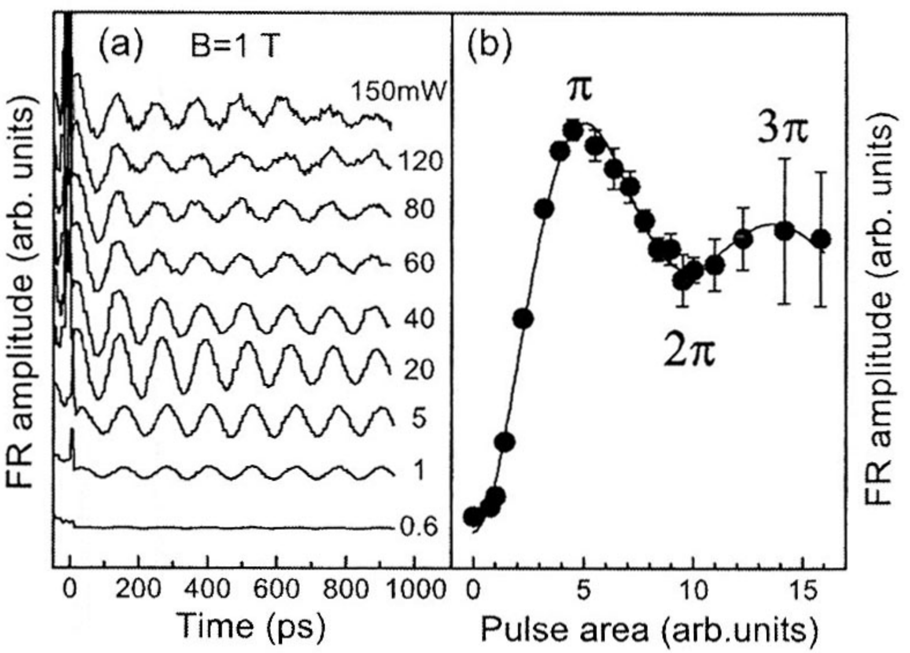
$E_0=5\times10^6$ V.m^{-1}

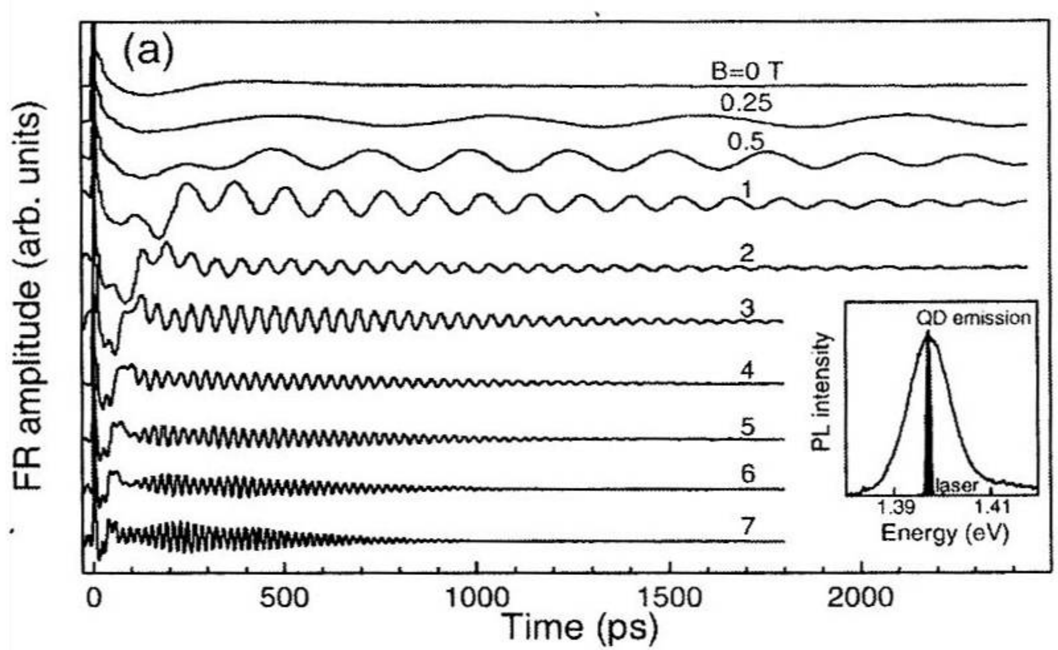
$E_0=4\times10^7$ V.m^{-1} (π/2 – pulse)
Rabi oscillations





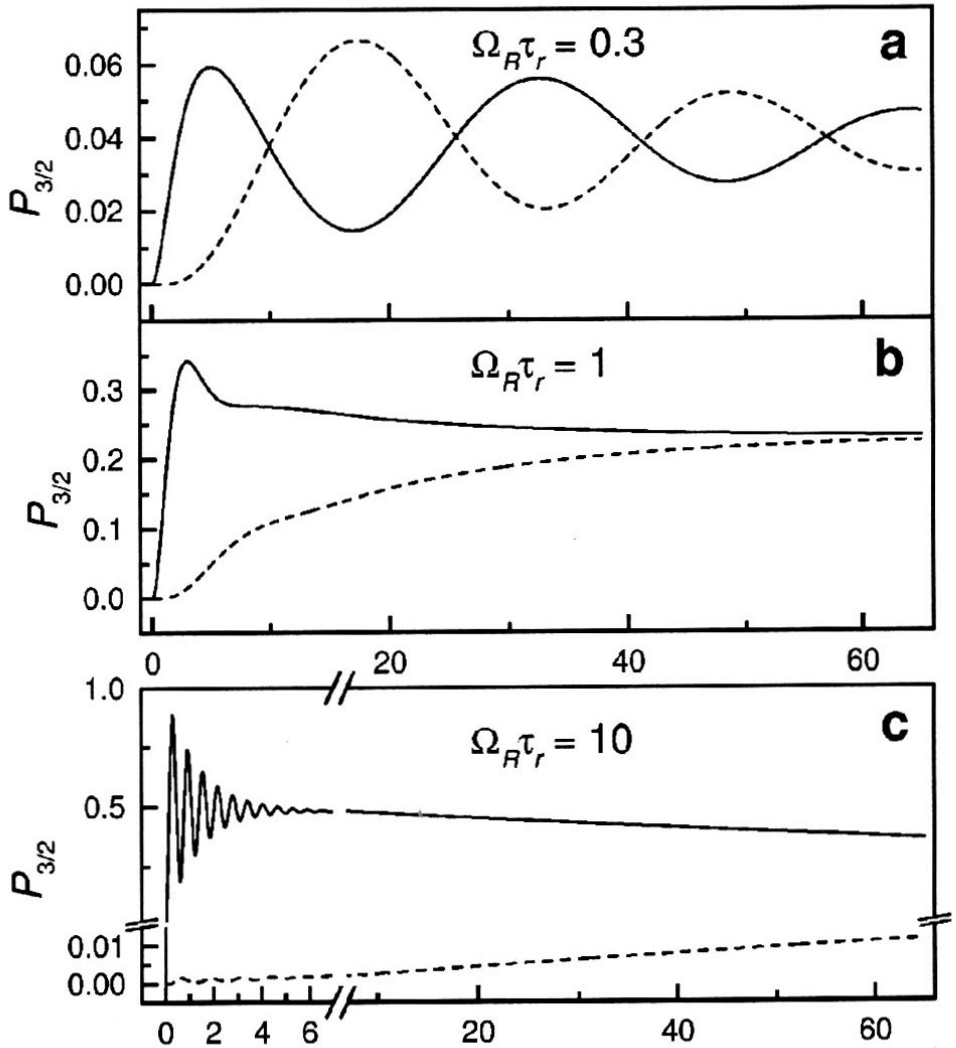
Trion optically-induced coherent spin dynamics (time-resolved Faraday rotation experiments)



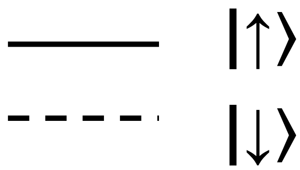


Greilich et al. , PRL 96, 227401 (2006)

Time dependence of the |3/2⟩ trion spin population (theory)



Shabaev et al. , PRB 68, 201305 (2003)



Summary/Outlook

A novel model of the optically-induced coherent spin dynamics in QDs:

- *Selective spin excitation with predefined helicity of the optical pulse demonstrated*

- *Rabi flopping of the population inversion and polarised Self-induced Transparency solitons numerically demonstrated*

- *Model for the non-equilibrium coherent optically-induced spin dynamics in QDs embedded in optical waveguides and semiconductor microcavities*

- *Beyond SVEA, RWA and rate equations approximations: valid for few optical cycle pulses*