Deterministic Writing and Control of the Dark Exciton State using Short Single Optical Pulses

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Abstract: We experimentally demonstrate deterministic optical writing of a quantum dot-confined dark exciton, in a pure quantum state using one optical pulse. We then control the spin state of this long-lived exciton using picosecond optical pulses.
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On-demand initialization and resetting of physical two level systems (qubits) and their coherent control are basic requirements for quantum information processing. Single half-integer spin based qubits such as nuclei, atoms, electrons, and holes are by far the most studied matter qubit systems. Since these spins are inherently degenerate their utilizations require application of external magnetic field, their initialization requires series of repeated operations and their full control cannot be achieved on shorter times than their Larmor precession period.

A dark exciton (DE) is an electron hole pair with parallel spins [1]. The DE has total integer spin of 2, with projections of ±2 on the QD growth axis, reflecting the difference in angular momentum and spin between the conduction and valence band states. Since photons barely interact with electronic spin, the DE is almost optically inactive and has a lifetime that is more than three orders of magnitude longer than that of the bright exciton [2].

We demonstrate for the first time that the quantum dot-confined DE [1] forms a long lived (more than 1 μs) integer spin qubit which can be deterministically initiated and fully controlled by short optical pulses, several orders of magnitude shorter than the life and coherence time (at least 100 ns) of this qubit. An absorption resonance to one out of the two DE eigenstates was identified using photoluminescence (PL) and PL excitation spectroscopy. The DE presence can then be detected optically via excitation to a spin-blockaded biexcitonic state [1, 3], which radiatively decays. The emission intensity of this decay is directly related to the population and spin state of the DE. Using this technique, we demonstrate Rabi oscillations in the DE pulse excitation intensity dependence. We identify the energy required for π and 2π pulses, thus demonstrating that the DE can be optically written on-demand.

Figure 1 displays the PL emission intensity from the biexciton as a function of the power and energy (inset) of the pump laser in the presence of the probe laser. The inset was recorded with continuous wave lasers for two rectilinear polarizations of the pump beam. In the main panel of Figure 1, pulsed pump-probe measurement at a repetition rate of 1MHz were used. Rabi oscillations are clearly observed.

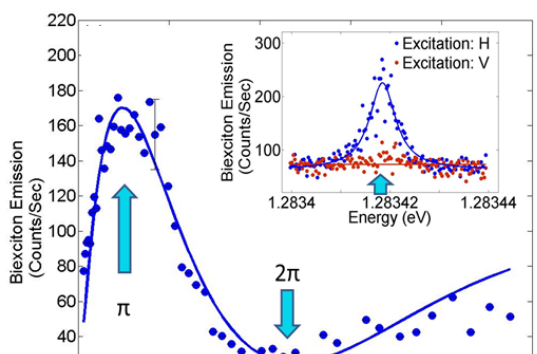

Figure 1: Deterministic generation of the DE (a) Probe spin-blockaded biexciton emission intensity as a function of the average resonant excitation power into the DE absorption resonance with pulse width of 60 ns. The power at which a π- and 2 π -pulse are obtained are marked by vertical blue arrows. The solid line represents a model fit of the Rabi oscillations. In the inset, the biexciton emission intensity as a function of the energy of the H (V) linearly polarized excitation into the DE optical transition is depicted by the blue (red) dots. The energy used for resonant, deterministic excitation of the DE is indicated by a blue arrow.

The pump pulse intensity, which corresponds to a π- and 2π-pulse, are marked by vertical blue arrows. Figure 1 therefore demonstrates that a proper combination of pulse energy, polarization, duration, and power deterministically generate the DE. A comparison between the intensity and temporal pulse width needed to obtain a π-pulse to the DE with that needed for the BE yields directly the ratio between the radiative lifetimes of both excitons. We independently verified in this way that the DE lifetime is more than three orders of magnitude longer than that of the BE.

This deterministic initialization of the DE is then used to demonstrate control of the DE spin state in a manner similar to the control of the bright exciton [4-6]. This control is described in Figure 2(a), where a right hand circularly polarized (R) control pulse rotates the DE spin from the eigenstate in which it was deterministically photogenerated to a coherent superposition of its two eigenstates, resulting in visible DE spin precession. In contrast, a horizontally linearly polarized (H) pulse (Figure 2(b)) does not result in such a rotation. Our novel demonstration of on demand DE initialization in a pure spin state by single optical pulse and its full optical control in the absence of external fields, suggest that the DE forms an excellent spin qubit, on par or even superior to the spin qubits formed by its constituents, the electron or hole separately.

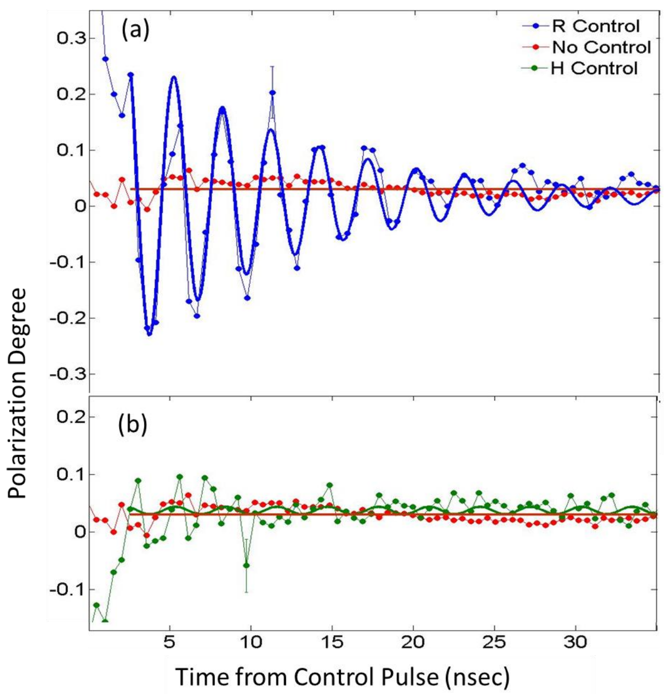

Figure 2: Experimental demonstration of the DE spin control (a) [(b)] The measured (points) degree of circular polarization of the emission as a function of time after the application of a R- (right hand circularly)- [H- (horizontal linearly)] polarized control pulse (blue) [(green)], compared to that measured in the absence of a control pulse (red). The solid line in (a) represents a decaying sinusoidal model fit. The polarization oscillations decay within ~20 ns due to the strong probe field.

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