# Robust Optical Inversion of the Excitonic Population of InGaAs Quantum Dots via Adiabatic Rapid Passage

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**Abstract**: We show population inversion in a semiconductor quantum dot with a chirped optical pulse via adiabatic rapid passage. This method is insensitive to variations in the dipole coupling and provides a new tool for preparing ensembles of quantum states.

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## 1. Introduction

Optical control of quantum states in a semiconductor system is a requirement for applications in quantum computation, single photon generation and studies of Bose-Einstein condensation. The control of the electronic occupation of a single semiconductor quantum dot has been shown by means of a resonant, transform-limited optical pulse through the phenomenon of Rabi oscillation [1]. However, control via Rabi oscillation is highly sensitive to the integrated pulse area $\theta = \int \frac{\mu \cdot E(t)}{\hbar} dt$ where μ is the dipole moment and $E(t)$ the electric field envelope of the exciting pulse.

Here, we demonstrate experimentally that the method of adiabatic rapid passage (ARP) [2] can be utilized for optical state preparation and is largely independent of variations in either dipole moment or optical intensity. In the Bloch sphere representation, in the rotating frame of the light field, interaction with a transform-limited pulse can be represented by the state vector of the two-level system precessing about the stationary field vector at the Rabi frequency, $\Omega_0$. For a linearly chirped pulse, the effective Rabi frequency $\Omega(\mathrm{t}) = \sqrt{\Omega_0^2 + (\alpha t)^2}$ now depends on the chirp rate α. The state vector will now precess around the moving field vector at the effective Rabi frequency. As long as the adiabatic conditions $\frac{\alpha}{\Omega(t)} \ll 1, \frac{|\dot{\Omega}_0|}{\Omega(t)} \ll 1$ are met the state vector will follow the field vector's evolution along the surface of the Bloch sphere. Thus, in the adiabatic regime, the state vector will follow the field vector from pole to pole, inverting the system regardless of variations in the dipole coupling.

The systems under study are InGaAs semiconductor quantum dots grown via the Stranski-Krastanow self-assembled method on an *n*-doped GaAs substrate. The dots are embedded in a photodiode structure with a semi-transparent Schottky contact allowing both optical excitation as well as electrical readout of the inverted population of the system. Single dots are isolated by sub-wavelength apertures in a metallic mask laid over the top contact.

As shown in Fig. 1A, various charged species of the excitonic structure of the dots were mapped through photoluminescence (PL) spectroscopy at biases from -0.2 V to +1.0V [3]. The PL signal was collected via a confocal microscope and spectrally resolved. In this voltage range, the radiative recombination rate is large in comparison to the tunnelling rate of the electron. The transition used for demonstration of ARP population transfer was the occupation of the neutral exciton from the crystal ground state. The biexciton transition was detuned by approximately 3 meV from the exciton while the bandwidth of the exciting pulse was 0.3 meV, thus justifying the application of a two-level quantum model to this system.

## 2. Methods and Results

As demonstrated in Fig. 1B, a grating pair was utilized to obtain a linearly chirped pulse with a FWHM of 15 ps from a transform-limited pulse with FWHM of 2 ps centered at the neutral exciton resonance of 1343 meV. The pulse area was scanned by incrementally increasing the incident power of the optical excitation. The excitonic population of the quantum dot was measured by the photocurrent of the device at -1.0 V bias to ensure that electronic tunnelling rates dominated radiative recombination. In the absence of competing tunnelling or decay paths, one electron should tunnel from an inverted quantum dot each pulse, giving an upper bound of the photocurrent of $ef$ where $f$ is the repetition rate of the pulsed laser and $e$ is the fundamental charge of an electron. For our system ($f$ = 76MHz), this would result in a theoretical maximum photocurrent of 12.2 pA.

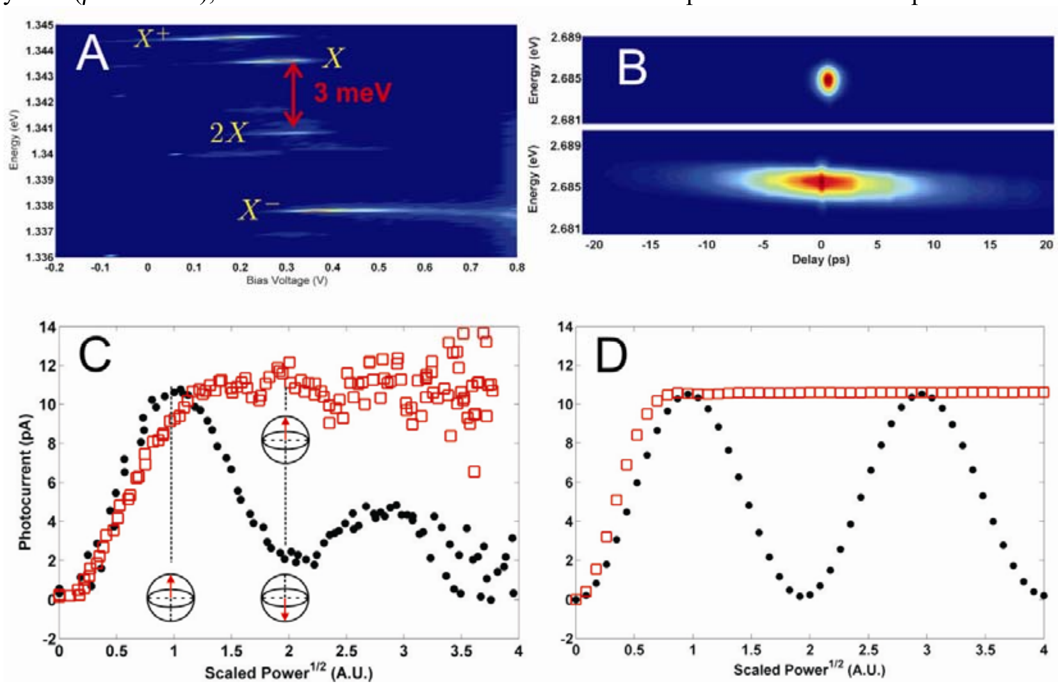


Figure 1: (A) The PL spectrum of the dot showing the exciton-biexciton detuning. (B) The auto- (top panel) and cross-correlation (bottom) of the transform-limited and chirped pulses respectively. (C) The measured photocurrent under excitation with the transform-limited pulse (black dots) shows Rabi oscillations while the chirped pulse (red squares) shows complete inversion beyond a critical intensity. The Bloch spheres represent the orientation of the state vector in the rotating frame of the laser field for specific pulse areas. In both cases, a linear background photocurrent is subtracted. (D) A numerical simulation on a model system under equivalent excitation shows the same photocurrent behavior.

As illustrated by Fig. 1C, the background-subtracted photocurrent for illumination with the chirped pulse differs markedly from that obtained with excitation by a transform- limited pulse. With the unchirped pulse, we see the expected damped Rabi oscillations in the photocurrent with respect to the square root of power (which is proportional to pulse area for a transform-limited pulse) [4]. Under chirped excitation, the photocurrent rises toward the theoretical upper bound and beyond a critical intensity, remains inverted, regardless of changes in increases in pulse power. The orientation of the state vector at selected points is shown in the inset Bloch sphere. For the transform-limited case, the state vector oscillates from the ground to the excited state periodically with variation in incident power. The chirped excitation, however, inverts the state vector which then remains in this condition. This robust inversion is a hallmark of an ARP process. Our results fit closely with numerical models of a system under the same excitation conditions assuming an excitonic recombination time of 1 ns and a tunnelling time of 300 ps.

### 3. Conclusions and Further Work

We have shown evidence of inversion via ARP of the excitonic state of a single InGaAs quantum dot using linearly chirped optical pulses. Unlike the method of Rabi oscillation, inversion with ARP does not require precise control over the dipole coupling between the quantum dot and the optical field, thus opening the possibility for quantum control over ensembles of quantum dots [5]. Such ensemble control has application in various contexts including inverting systems with structures leading to deterministic single photon generation [6] and creating tailored population distributions for studying polariton electrodynamics in microcavities [7].

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