Coherent Acoustic Orbital Control of Diamond NV Center Excited States

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Abstract:

The spectrally narrow, spin-dependent optical transitions of nitrogen-vacancy (NV center) defects in diamond have been shown to be a promising platform for quantum networking. The entanglement generation rates of such networks suffer from spectral diffusion that originates from electric field fluctuations in the diamond, which couple to the excited state orbital doublet and alter the optical frequencies. With the motivation of better understanding how orbital decoherence can be overcome, we investigate quantum control of the excited state orbitals using gigahertz frequency strain. We show that coherent, multi-phonon orbital Rabi oscillations can be acoustically driven on nanosecond timescales. Additionally, we investigate orbital Rabi splitting in spectroscopy, finding good agreement between the measured orbital Rabi rate found by the two detection methods.

Summary of Research:

Diamond NV centers are a promising platform for quantum networking applications owing to their spectrally narrow, spin-preserving optical transitions at cryogenic temperatures [1]. Spectral diffusion of the optical transition frequencies decreases the entanglement generation rate [2,3]. Spectral diffusion originates from fluctuations of the local electric field environment of the defects and the coupling of these electric field fluctuations to the excited state orbital doublet which alters the optical transition frequencies and diminishes coherence [4].

Our recently published work studying the correlations between spectral diffusion and other physical parameters of the NV center found correlation with static strain [5]. Related to this, we have previously studied the coupling of GHz frequency acoustic waves to the excited state orbitals [6]. These results indicate that for some NV centers the optical transitions may be stabilized by coherently driving the excited state orbital transition using acoustic waves. With this idea in mind, we set out to demonstrate coherent acoustic orbital control in the time domain.

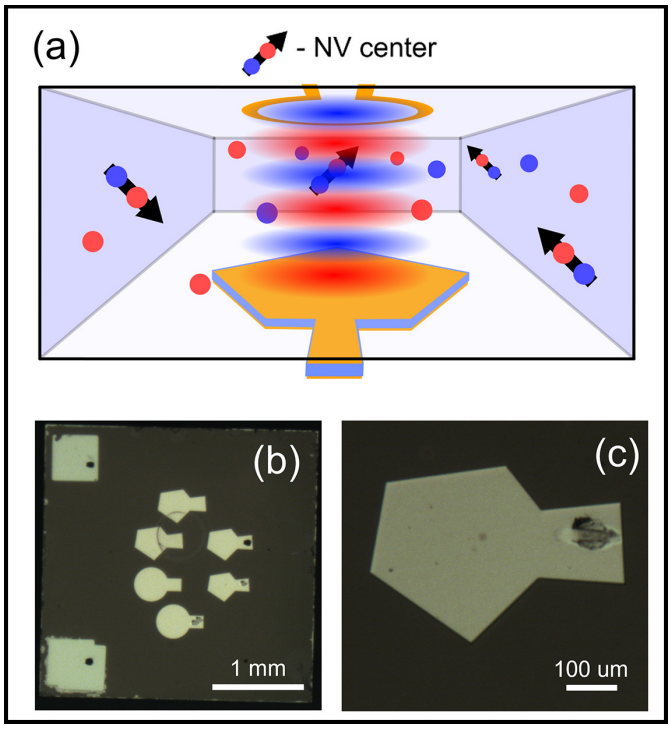

Figure 1: (a) Schematic of HBAR-on-diamond device for acoustic orbital control. HBAR transducer (orange pentagon) on diamond surface launches GHz frequency strain waves (red and blue ovals) into diamond bulk where the dynamic strain interacts with bulk NV centers. (b,c) Optical micrograph of finished HBAR-on-diamond device showing several finished HBARs on the diamond chip.

Our sample (Figure 1) is a type IIa diamond with individually addressable single NV centers formed via electron irradiation and subsequent annealing. On one diamond surface we fabricated a high-overtone bulk acoustic-wave resonator (HBAR) capable of launching GHz-frequency strain waves into the diamond bulk.

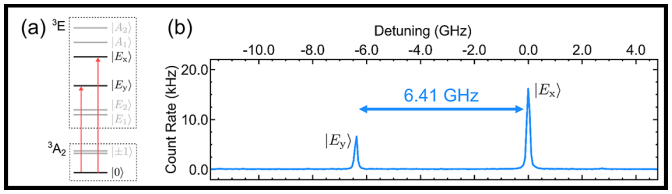

Figure 2: (a) Spin-preserving optical transitions of the spin-0 subspace (red arrows) of the NV center. (b) Laser-frequency swept PLE spectroscopy of a single NV center showing 6.41 GHz orbital splitting.

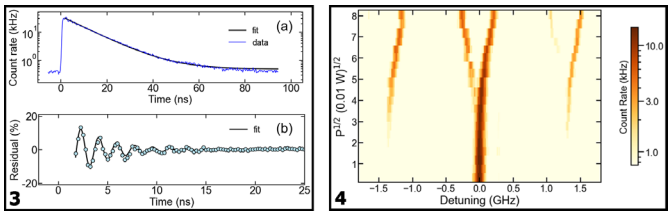

Figure 3, left: (a) Time-resolved histogram of photons emitted from our defect with respect to 1 ns resonant laser pulses (blue curve) while the HBAR is mechanically driven at 1.29 GHz. Exponential fit (black curve) used to remove exponential decay and extract residual oscillation. (b) Residual oscillation showing ns-scale precession of the orbital states in the strain field. Black fit is to a decaying sinusoid. Figure 4, right: (a) Frequency-swept PLE near the Ex transition versus acoustic drive power showing orbital splitting with increasing acoustic drive power.

The HBAR is formed by sandwiching a piezoelectric layer in between metal electrodes. The bottom electrode layer ([Ti (15 nm)/Pt (90 nm)] was deposited using the AJA Sputter Deposition system. A 1.2 μm thick layer of piezoelectric zinc oxide was then sputtered using equipment the Cornell Center for Materials Research. Finally, the top metal electrodes ([Ti (15 nm)/Pt (180 nm)] were fabricated by using the Heidelberg Mask Writer - DWL2000 to make the mask, the GCA 6300 DSW 5X g-line Stepper to write the pattern, and the AJA Sputter Deposition system to deposit the metals. After lift-off the device was wire bonded to our cryostat microwave feed lines using the Westbond 7400A Ultrasonic Wire Bonder.

We characterize the static strain splitting of a single bulk NV center in the diamond by performing photoluminescence excitation (PLE) spectroscopy [7]. We tune a red laser (~637.2 nm) across the resonant optical transitions of the NV center while counting photons emitted into the phonon sideband. The spin-preserving optical transitions are from orbital singlet, spin triplet ground states to orbital doublet, spin triplet excited states [4]. All measurements are carried out in a helium flow cryostat at 7 K. We focus solely on the spin-0 subspace. PLE spectroscopy of our defect reveals a 6.41 GHz splitting between the spin-0 orbital excited states which results from static strain in the diamond (Figure 2).

We perform time-domain resonant orbital driving experiments by tuning a red laser (~637.2 nm) onto resonance with an optical transition between the spin-0 ground state and one of the spin-0 orbital transitions (Figure 3). While continuously driving our acoustic resonator at 1.29 GHz (such that we excite orbital transitions via a 5-phonon drive) we provide 1 ns resonant laser pulses and record the arrival time of emitted photons relative to the excitation laser pulses. We observe an expected exponential decay of photoluminescence resulting from spontaneous emission as the defect leaves the excited state, and a residual photoluminescence oscillation which results from coherent orbital oscillations driven by the HBAR.

We confirm that these time domain oscillations are the result of the acoustic driving by performing PLE spectroscopy in the presence of acoustic drive (Figure 4). We observe a splitting of the PLE spectrum as the acoustic driving amplitude increases which results from coherent orbital driving. The splitting of the PLE spectrum from acoustic drive matches well with the frequency of the time-domain orbital oscillations, confirming that they originate from the same physics.

Conclusions and Future Steps:

Our results indicate that the excited state orbital doublet of NV centers can be coherently driven via acoustic drive. We confirm that our observed oscillations in the time domain match with the splitting observed in resonant optical spectroscopy under acoustic drive. Coherent orbital control will enable future studies of orbital and optical coherence of NV centers [8] under acoustic drive, where we can quantify the orbital and optical coherences and investigate orbital dynamic decoupling.

Our manuscript on time-domain coherent acoustic orbital control is currently under preparation.

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