State Preparation of Polarized Nuclear Spin States for the Quantum Diamond Processor

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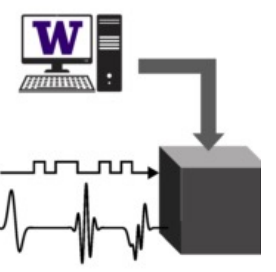
State Preparation of Diamond Quantum Processor



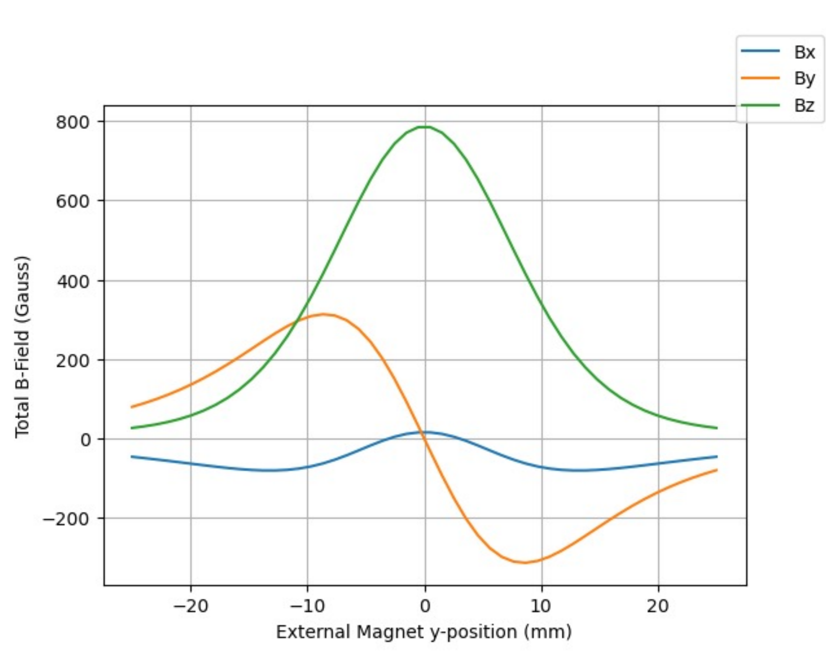
- The QT(3) lab plans to build a small-scale quantum control register for teaching and testbed purposes.
- The diamond quantum processor is a collection of qubits consists of electron spins and nuclear spins of nearby atoms of nitrogen vacancy (NV) centers in diamond.
- State initialization is an essential step for any quantum control protocols. This requires preparing the qubit state to a known state on-demand.
- This project aims to initialize nuclear spins near NV centers to form a small quantum register with electron spins for further quantum control protocol.

Project Background

- The nuclear spin of NV centers has long coherence time as long as 1 second at room temperature, which enables intriguing experiments including entanglement and teleportation between different nuclei, coherent control, quantum error correction, and Bell' inequality test [1].
- Nuclear spin state readout is achieved through optically detected magnetic resonance (ODMR) when a microwave field sweeps across the spin transitions and record the photoluminescence (PL) signal intensity. Spin transitions between m_s=1 and m_s=0 can be differentiated by monitoring the differences in photoluminescent intensities.
- This project is limited to the conditions of room temperature operation, small external magnetic field (<1 Tesla), above-band optical excitation, simple radio frequency (RF) pulse sequence (on or off). The scheme used to polarize nuclear spins follows [2] to establish excited state level anti-crossing (ESLAC) with an external magnetic field of 500 Gauss aligned to one NV axis, when different nuclear spin states are mixed and preferentially transferred to one spin state.
- The nuclear spin species available to be polarized is ^{14}N that has three nuclear spin orientations m_I=-1, 0, 1.

Magnetic Field Simulations

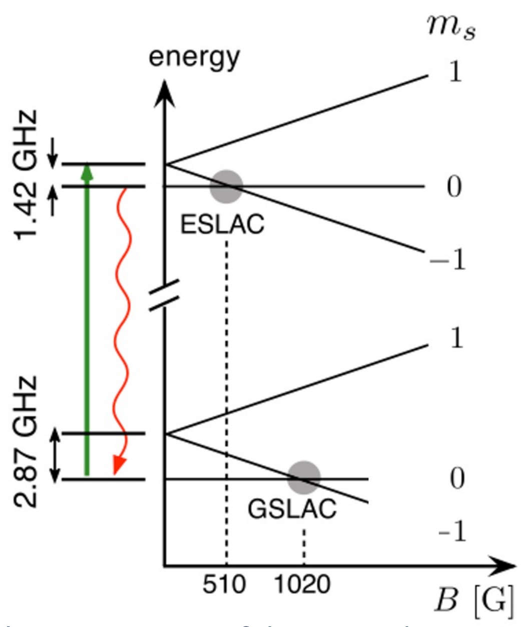
- ESLAC takes place at around 500 Gauss, and decent polarization can be obtained from 420-580 Gauss [2].
- Magnetic field strength is simulated using the magpylib Python package to estimate the field strength generated by permanent magnets to aid alignment of the external field to one NV axis.
- The simulated magnetic field accounts for two N52 grade neodymium permanent magnets with ½ inch diameter and length.



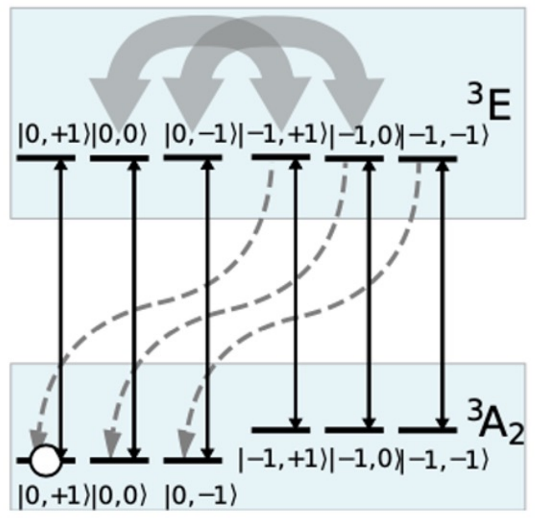
- Magnetic field simulation indicates that around 500 G field strength is accessible around 8mm away from the magnet surface.

Nuclear Spin Polarization through ESLAC

- Level anti-crossings of NV centers occur at nonzero magnetic fields where the Zeeman splitting of m_s= -1 energy level tends to cross with m_s= 0 energy level, but the crossing is avoided due to to spin–spin interactions.
- Strong hyperfine interaction between the electron and the nitrogen nuclear spin in the excited state (~ 20 times stronger than that of the ground state) leads to energy-conserving nuclear spin flip-flops between the mixed electron-nuclear states[2].



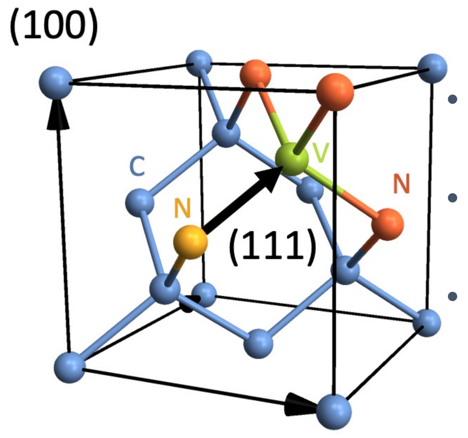
Level anti-crossings of the ground state (GS) and the excited state (ES) and corresponding field strength reproduced from [4].



Electron-nuclear spin state mixings at the excited state level anti-crossings reproduced from [3].

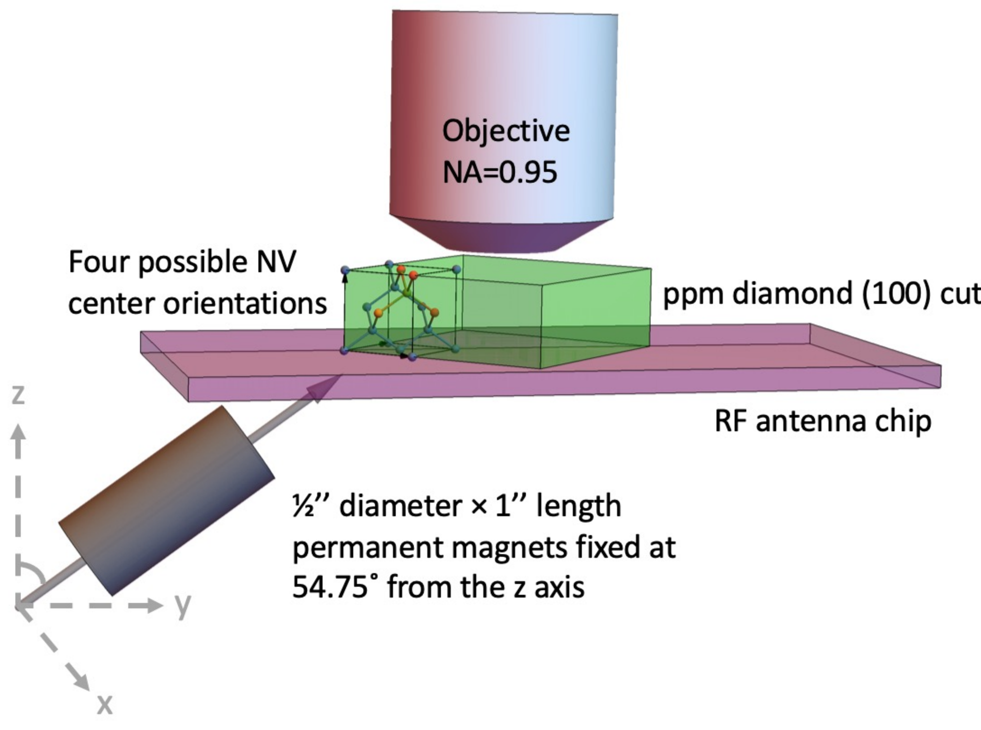
- ESLAC occur at 510 Gauss, where electron-^{14}N nuclear spin state $|m_s, m_I\rangle = |0, 0\rangle$ is mixed with $|-1, 1\rangle$, and $|0, -1\rangle$ with $|-1, 0\rangle$. The population of unmixed states $|0, 1\rangle$ and $|-1, -1\rangle$ are preserved.
- Since electron spin state $|m_s|$=1 tends to relax to m_s=0 under optical pumping, the electron-nuclear spin state ends up in $|0, 1\rangle$ after a couple optical pumping cycles and the nuclear spin state of ^{14}N is polarized to m_I = 1.

Alignment of One NV Axis to an External Magnetic Field



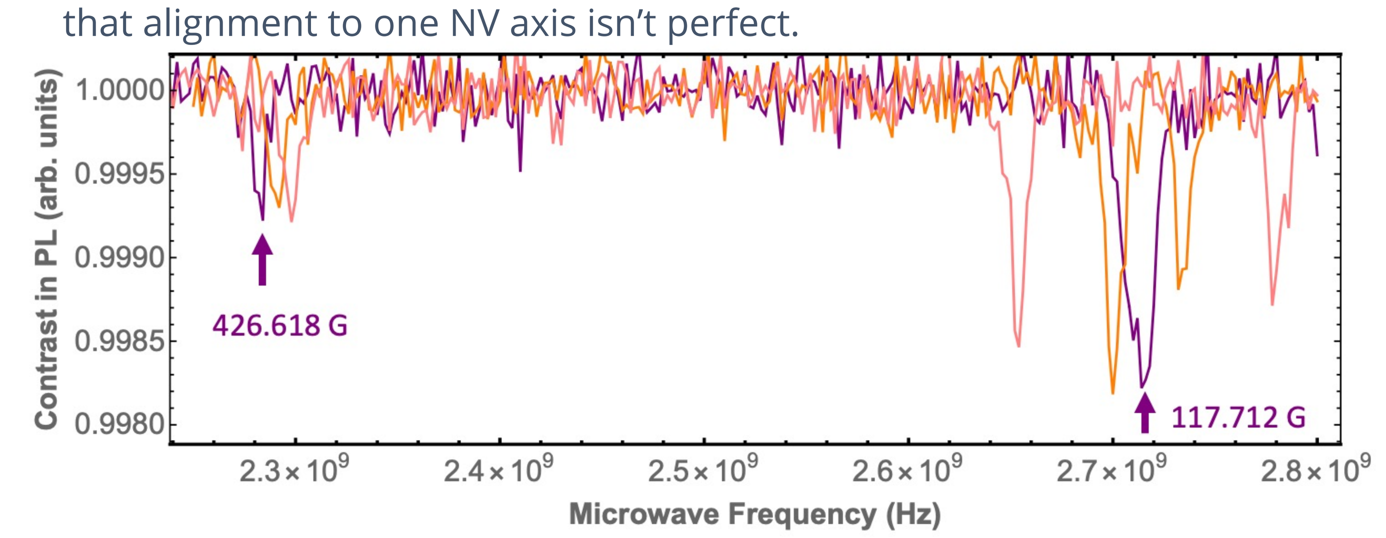
- Good alignment within a few degrees is necessary to observe nuclear spin polarization [2].
- The diamond sample available contains part per million (ppm) nitrogen and is cut along the (100) direction. The edges are {100}.
- The aim is to align an external magnetic field to the NV axis along (111).

- The diamond sample is rotated 45 degrees in the x-y plane and a permanent magnet is fixed at half of the C-C bond angle (109.5 degrees) from the optical axis in the z-direction.
- The sample is glued onto an RF antenna chip attached to the edge of an x-y-z stage. The magnet is mounted to an x-y stage and a tip-tilt stage with a fixed angle 54.75 degrees from the z-axis.

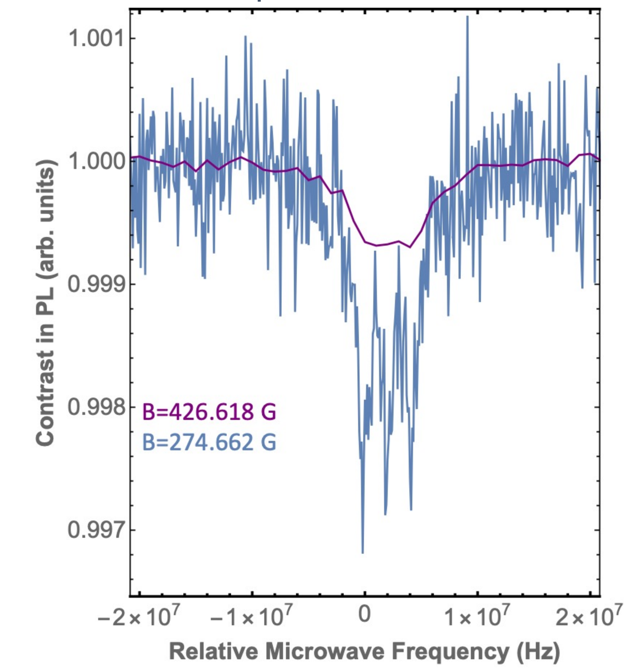


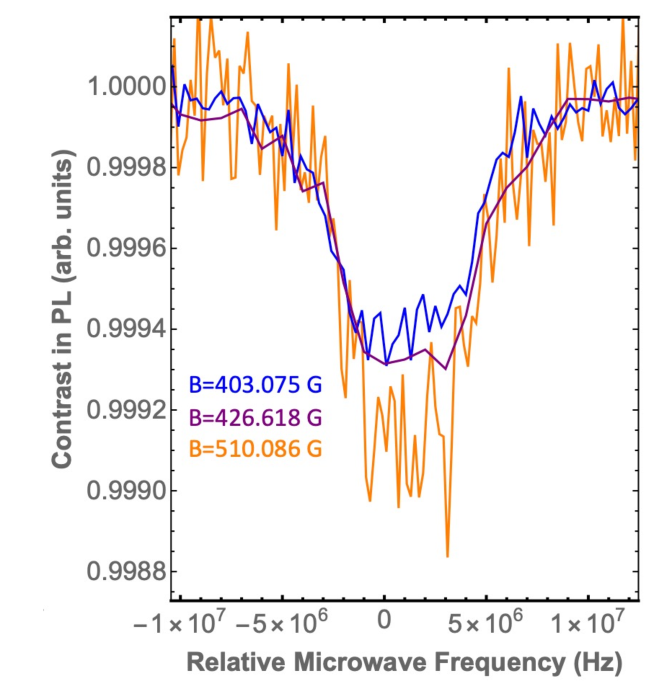
ODMR Results and Analysis

- When an external field is well-aligned with one NV axis, four dips in the ground state ODMR spectra are expected as one crystal orientation sees the largest field. The projection of the field strength on the other three orientations is the same, therefore their ODMR dips overlap.
- The purple data below shows two dips in half of the ODMR spectra when the external field is well-aligned with one NV orientation. The pink and orange data show 3-4 dips in a half spectra, suggesting poor alignment of the field.
- The discrepancy between the expected dip position (2.68 GHz) from actual dip position (2.715 GHz) based on the measured largest field strength suggests that alignment to one NV axis isn't perfect.



- Nuclear spin polarization is manifested as one dip when ESLAC takes place at around 500 G, instead of three dips corresponding to three possible ^{14}N nuclear spin orientations.





- (left) Nuclear spin polarization at 426.618 G shown by purple line, while the blue data shows unpolarized nuclear spins at 274.662 G.
- (right) All three spectra show some degree of nuclear spin polarization, while the purple data displays the best alignment to the external field when single nuclear spins are not resolved. This result suggests that good alignment is crucial in addition to sufficient field strength to polarize nuclear spins through ESLAC.

Future Work

- Check that the nuclear spin polarization dip is not power-broadened.
- Incorporate power transmission of the RF antenna and characterize the degree of polarization by quantifying the contrast in ODMR signal as a function of field strength, alignment, pulse duration, etc.
- Vary field strength while maintaining good alignment to one NV orientation.

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