Nitrogen Vacancy Centers in Diamond

Purpose

Nitrogen vacancy (NV) centers in diamond are solid state defects that are useful in quantum information applications due to their long spin coherence times at room temperature, their atom-scale size, and the ease with which their electronic spin state can be optically prepared and measured using an off-resonance laser. In this lab we will use a home-built confocal microscope to measure single NV centers to demonstrate their utility for quantum sensing and quantum information applications.

Background

The NV center defect consists of a substitutional nitrogen atom taking the place of a carbon atom with an adjacent vacancy in the diamond lattice structure. With low enough densities of these defects in a diamond, individual NV centers can be optically resolved and manipulated.

Methods of quantum sensing and computation often require low temperatures and/or high vacuum; the NV center's long electronic spin coherence times at room temperature and under ambient conditions lift these stringent requirements and make it a useful candidate for effective, relatively simple demonstration of standard quantum gates and measurement sequences. By finding resonant frequencies through continuous wave electron spin resonance (CW-ESR) and applying pulse sequences at these frequencies (Rabi, Ramsey), we can both manipulate the spin state of the NV ensemble and learn about the NV centers' coherence times and surrounding environment.

The NV center can have multiple stable charge states, but almost all quantum science applications make use of the negatively charged NV center (NV-), which has a spin-1 triplet electronic ground state. The spin sublevels that make up this ground state are given by the projection of the total electronic spin along the nitrogen-vacancy axis of the NV defect, $m_s=0$ and $m_s=\pm1$. The $m_s=0$ state is the lowest in energy, and is split from the $m_s=\pm1$ states by the zero field splitting energy $D \approx h \times 2.87$ GHz, where h is Planck's constant. The $m_s=\pm1$ states are degenerate at zero field, but the degeneracy can be lifted by applying a magnetic field B_z along the NV axis, lifting the degeneracy and enabling us to select a subspace consisting of $m_s=0$ and either $m_s=+1$ or $m_s=-1$ that can serve as a qubit.

Experimental Set-up

Optical Setup

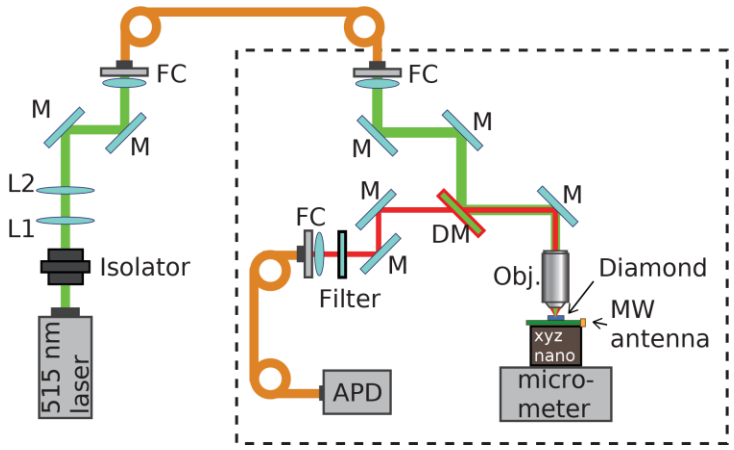

Figure 1: Diagram of the optics of the setup.

- **Laser preparation:**
  - **Laser:** 515 nm (green) solid state laser. The on/off state of the laser can be controlled by TTL pulses via an SMA connector on the back of the laser head, allowing for fast (nanosecond timescale), precise control of the laser's state.
  - **Isolator:** Protects the laser from back reflections from other optical elements in the setup.
  - **Lenses (L1, L2):** These two lenses change the size of the laser beam, so that it couples into the fiber. Focal length L1 = 30 mm, L2 = 50 mm.
  - **Fiber coupler (FC):** Couples free space laser beam into fiber
  - **Mirrors (M):** Dielectric mirrors
- **Confocal microscope:**
  - **Dichroic Mirror (DM):** A mirror that reflects wavelengths of light below 638 nm and transmits wavelengths of light above 638 nm, allowing the separation of the green excitation and red fluorescence
  - **Filter:** Optical long pass filter to only allow light above 638 nm to transmit, which isolates the NV's signal
  - **Avalanche PhotoDiode (APD):** A single photon counting device to collect counts from the NVs.
  - **Objective (Obj.):** A 40X Nikon objective used to focus light at the sample.

- **Microwave antenna:** The antenna is built into a pcb board and delivers the microwave pulses used to manipulate the NV's spin state.
- **XYZ Nano Positioner:** A piezoelectric device which allows precise positioning in x, y ,and z directions to ~ nanometer lengths.
- **Micrometer:** A mechanical device to more roughly position the diamond with respect to the objective.

Electronic Setup

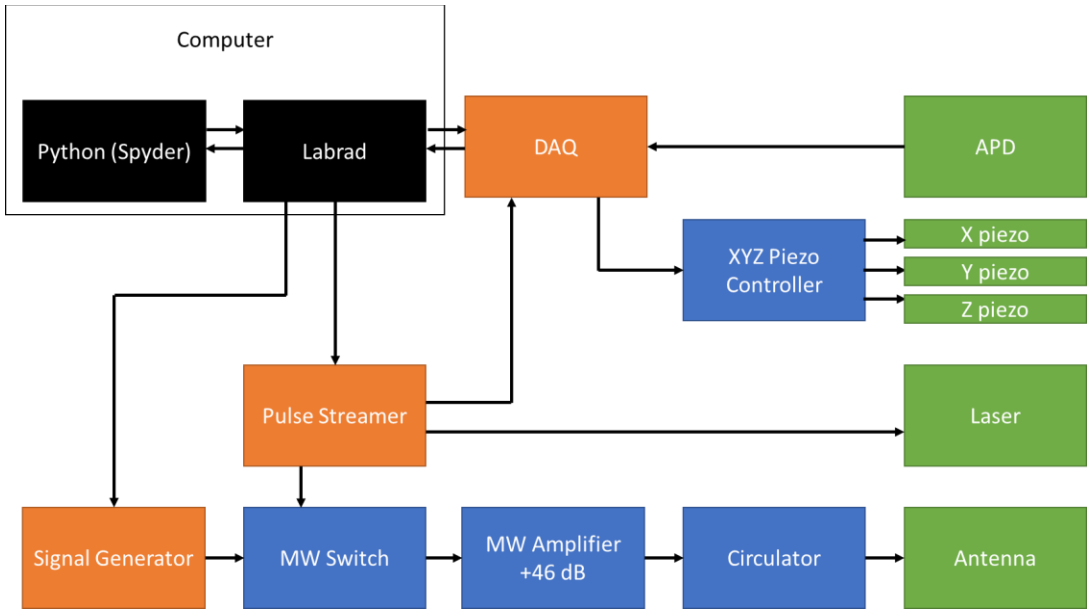

Figure 2: Diagram of the electronics and software of the experiment

Software

- **Python (Spyder):** we use Python to run experiments, and specifically we use Spyder to run the Python scripts.
- **Labrad:** We use Labrad, a networking framework for lab experiments, which sets up servers for the equipment used in our lab and communicates with them. Labrad will communicate with the signal generator to set its amplitude and frequency, the DAQ to trigger and acquire data collection, and the pulse streamer to run pulse sequences**.** The

user interface is accessed using a desktop shortcut to a Chromium window, as well as three terminal windows that are running in the background.

Hardware

- **Pulse Streamer:** The pulse streamer sends precisely timed TTL pulses to the DAQ to trigger data acquisition, the laser to turn the laser beam on and off, and to the microwave switch to turn the microwave signal on and off.
- **DAQ:** Data Acquisition (DAQ) takes the signal from the detector and digitizes it for use on the computer.
- **APD:** An avalanche photodiode, which can collect counts from individual photons, used to detect fluorescence from the NVs.
- **XYZ Piezo Controller:** The controller that positions the XYZ nano piezo. It receives analog voltage signals from the DAQ, which receives commands from Labrad.
- **Signal Generator:** This generates the microwave signal, and is the input to the RF switch.
- **MW Switch:** The TTL pulses from the pulse streamer precisely control the RF switch. The signal generator cannot turn the pulses on and off fast enough for our needs, so the MW switch allows faster control of the MW signal.
- **MW Amplifier:** Amplifies the signal from the switch.
- **Circulator:** Protects the amplifier from back reflections.
- **Antenna:** Uses the signal from the amp to generate MW near the diamond.

Experiment 0

Imaging and finding and NV center

Introduction/Theory:

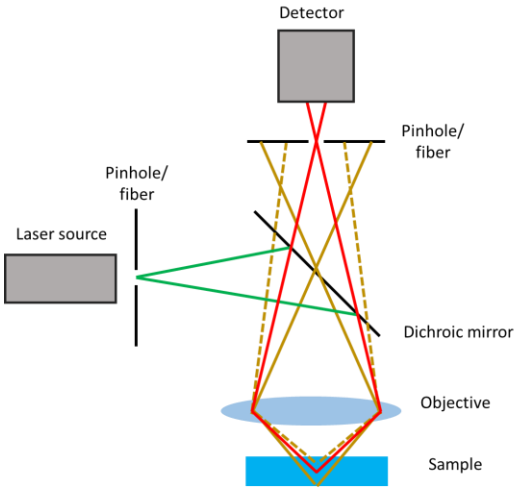

Figure 3. Confocal microscope

You will be running experiments on the spin states of a single NV in a diamond. Before we run measurements, we first need to identify a single NV.

To image and measure individual NV centers, you will use a confocal microscope. This type of microscope improves the optical resolution and contrast by spatially filtering out-of-focus fluorescence at the sample, as illustrated in Fig 3. The excitation (green light) is tightly focused at the sample with the objective lens (down to about 300 nm in x and y for our 515 nm light). The fluorescence from the sample (red) is focused through a pinhole (or a single mode fiber in our setup) and sent to the detector. Because of the detection pinhole, only fluorescence light from the same focal spot/plane of the excitation light is collected, eliminating background light and reducing the resolution significantly.

Confocal microscopes do not collect light across the whole sample, like conventional wide-field microscopy. Instead, light from one “point” is collected. To take an image, the sample needs to be moved with respect to the objective. In this experiment, an XYZ nano positioner is used to move the diamond sample. Any image or spatial scan is then formed, point by point, moving the nano positioner for each point.

Before starting the experiment, take the top off the black box containing the confocal microscope and look at the optics. Identify the different optics that correspond to the optics diagram of Figure 1.

(**Note before continuing**: All adjustments for experiments will be made in Spyder. You should not have to touch the optics or electronics. Please exercise caution throughout as to not bump the table or the setup as this can lead to loss of signal in the optical setup.)

Procedure:

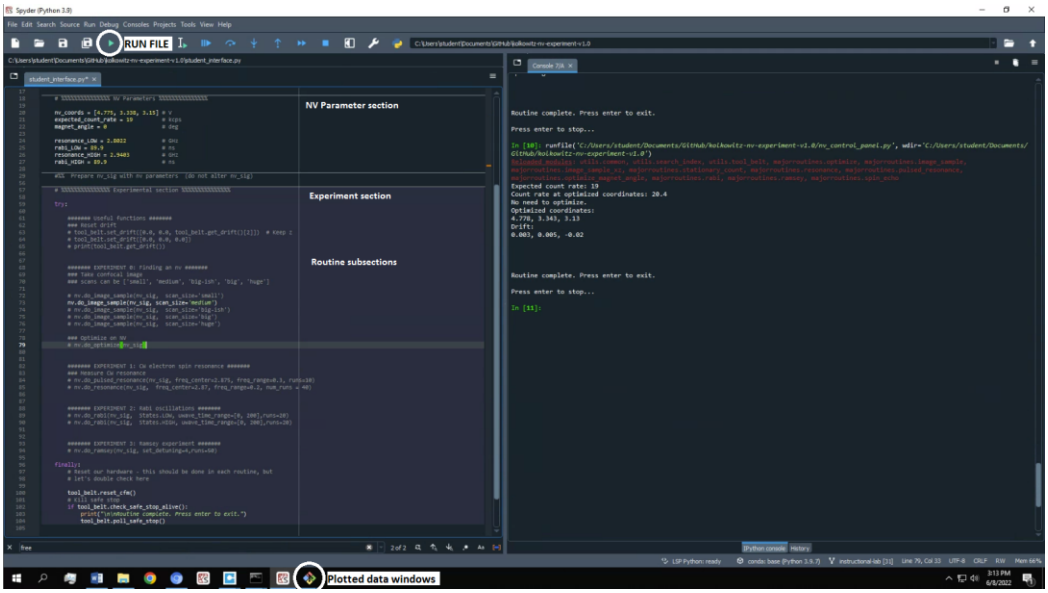

Figure 4: Spyder window.

1. Identify the power extension cord for the APD, which will turn the APD on or off. The APD is extremely sensitive to light, so it is important to always have the **APD turned off if the box for the confocal microscope is open and the room lights are on**. Once you are ready to run experiments, put the lid back on the confocal microscope box, and you can turn the APD on. Lights can be on with the APD **if** the box is closed.

2. Now we turn to the software side of the experiment. If Spyder is not open already, open Spyder.
3. Spyder is a convenient interface for using Python. There should be two main regions in the Spyder window, as seen in Figure 4.
    a. The left area displays the python file.
    b. The right area displays the "console", which is an active python interface, and will output information from the python file once it is run.
4. The file you will be using is called "student_interface.py". Make sure it is the file that is currently open.
5. This file will run all the experiments for this lab. There are two main sections to the file:
    a. The *NV Parameters* section is where you will input information about the NV you find and will work with, including its position, the fluorescence count rate, and spin state parameters.
    b. The *Experiment* section hosts the different **routines** you will run, and it is split into subsections. Most of the routines are "commented out", where a # symbol at the beginning of the line excludes it from actively running.

       Note: the key command to comment/uncomment a line is pressing *`CTRL + 1`*. You can highlight multiple lines and comment/uncomment them all together.

6. We will run a confocal scan first, which is the routine called "**image_sample**". Under *Experiment 0*, uncomment the line

   `"nv.do_image_sample(nv_sig, scan_size = 'medium')".`

   To run the python file, click the *green triangle icon* in the upper banner of the Spyder window.

7. Another window on the computer will open (the icon looks like this ), which plots the image as it is being taken, one point at a time.
8. Once the image routine is complete, the console will display:

   `Routine complete. Press enter to exit.`

   `Press enter to stop...`

   Which requires you to click in the console and press `Enter`.

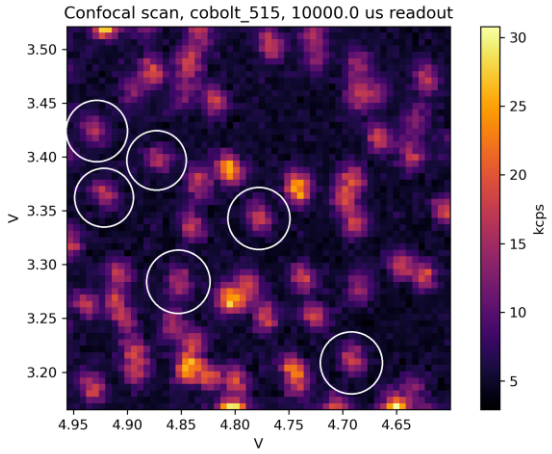

Figure 5: Example of confocal image of NVs, circling good candidates for well isolated, single NVs

9. You should see many NVs in your image, similar to Figure 5. You want to identify a single NV, usually between 15 - 25 kcounts per sec (kcps). You also want it to be isolated from surrounding NVs. Some good candidates are identified in Figure 5. If the NVs appear very out of focus, you may need to run an xz scan to find a better z position.
10. Once you have found what looks like an isolated single NV, click on it in the plot window. The x and y coordinates are then printed in the console.
11. Copy these coordinates and put them in the first two values of the parameter `nv_coords` list.
12. You can take additional images at different scan sizes. They should now be centered on your NV.

Next, we want to find the precise coordinates of this NV, and record its typical brightness. We will run **do_optimize** for this, which runs spatial scans in the x, y, and z directions about the nv_coords.

13. Uncomment `nv.do_optimize` and comment out all other routines.
14. Make sure the value for the parameter `expected_count_rate` is set to `None`.
15. Lastly, uncomment the line `tool_belt.reset_xy_drift()`.

    Note: when you run a routine, you pass nv_coords based on the original image you took, however optics can drift over time and those coordinates slowly change. Optimize identifies the new location of the NV, and equates the difference between the nv_coords

value, the “drift”. It then saves the x, y, and z drift values in Labrad, and the next time you run a routine, it will then account for the drift by adding the values it saved to the nv_coords you pass. By setting the x and y drift as zero in this step, we make sure we initially optimize on the NV you chose, and the drift from the previous lab group doesn’t add to your current NV coordinates. Note that the images use the real coordinates, not including drift. Setting the xy drift to zero first assures that the coordinates from the image do not need to be adjusted for drift, making finding an NV easier.

16. Run the python file to optimize. The plotted data should show three panels, each with a clear peak indicating where the NV is located in each direction. The console will return something that looks like:

```
Expected count rate: None

Initial check of count rate at passed coords: 19.4

Expected count rate not set. Optimizing...


Count rate at optimized coordinates: 17.2

Optimization succeeded! (No expected count rate
passed.)

Optimized coordinates:

-0.318, 0.309, 5.80

Drift:

0.001, -0.000, 0.04
```

    The line highlighted above is the count rate at the optimized coordinates for the NV, which we want to save. If you do not get one isolated peak in z, there may be another NV at a slightly different depth in the diamond. If this is the case, it is best to try again with a different NV.

17. Copy the highlighted value into the NV parameter `expected_count_rate` in the python file. The routines use this count rate to make sure it is optimizing on the NV, and not to something more/less bright.
18. Once you are done, comment out the line `reset_xy_drift()`.

Analysis:

1. The confocal images you took are plotted with the voltage values of the piezo. The piezo takes voltage values from 0 to 10 V, spanning a range of 200 um. With that information, what is the conversion of the piezo voltage to physical distance? Using the value you calculate, what is the "size" of an NV in your images? Does this correspond to the actual size of the NV defect?
2. It is typical for the objective to shift its focus with respect to the sample, and it is easy to lose the NV you are working with between days. It is recommended that you take a large scan to help find the NV in the following lab days.
3. Data is saved automatically on the computer in the location: `C:\Users\student\Documents\LAB_DATA\pc_fzx31065\branch_instructional-lab`. Make sure you can find where this is on the computer. Each routine has its own folder, with subfolders for each month. The figure is saved as a png, and raw data is saved as a python dictionary txt file.

Experiment 1

Continuous Wave - Electron Spin Resonance (CW-ESR)

Introduction/Theory:

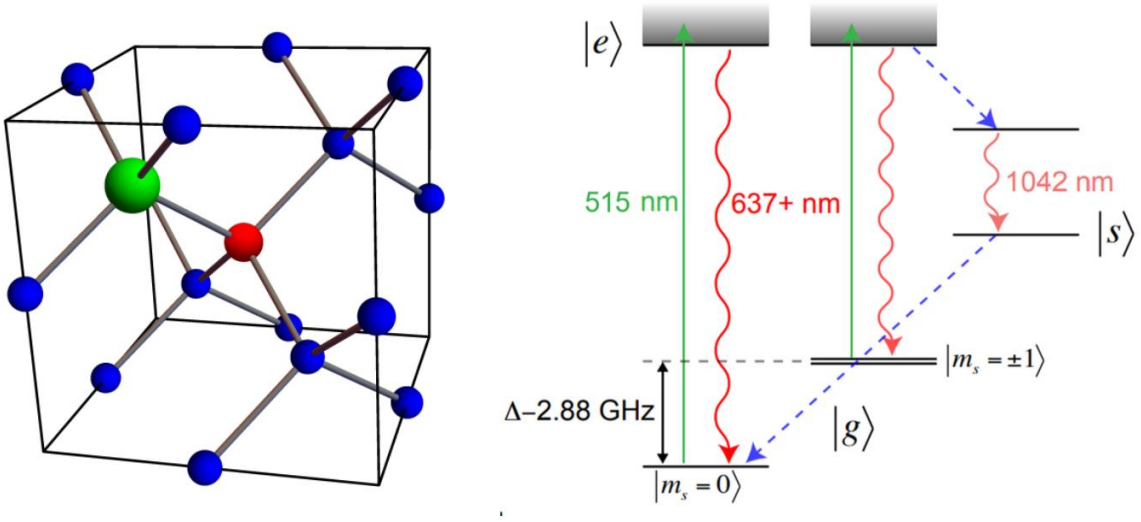

Figure 6: (Right) Atomic structure of the NV center where blue represents carbon, red is nitrogen, and green is vacancy. (Left) Energy level representation of NV(-).

The NV(-) energy structure has a ground state, optical excited state, and a singlet state manifold as seen on the energy diagram above. The applied 515nm laser pumps the ground state electron into the excited state through the "phonon sideband" of the NV center. The excited electron will then relax in one of two ways:

1. It can relax directly into the groundstate and emit a 637nm photon or a lower energy photon (red light, which is detected by the photodiode) and some phonons. This decay pathway preserves the electronic spin state.

2. It will relax non-radiatively into the singlet states and emit a 1042nm photon (infrared), which is not detected by the photodiode. Relaxation into the singlet manifold is mostly from the $m_s=\pm1$ excited states, and decay from the singlet lower singlet state into the groundstate is primarily into $m_s=0$.

This has several consequences. First, by simply illuminating an NV center with 515 nm laser light, the electronic spin state will be optically pumped into the $m_s=0$ state. Second, because the lower lying singlet state *s* is longer lived (~300 ns) than the excited state *e* (~10 ns), an NV can temporarily become shelved there and will go dark, while an NV in the ground state *g* can be re-excited into *e*. Combined with the preferential decay into the singlet manifold from $m_s=\pm1$, this makes the $m_s=0$ state ~30% brighter than the $m_s=\pm1$ states.

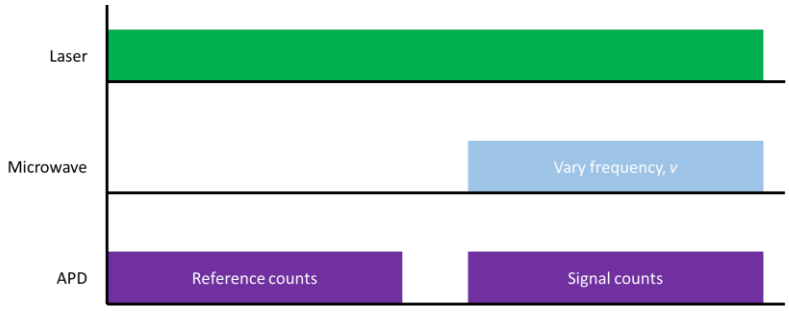

Figure 7: Sequence for CW-ESR

For CW-ESR, the 515 nm laser is left on continuously, and while collecting the fluorescence (+638 nm) signal counts, the MW is left on for the entire duration, at a frequency, *v*, that is changed each repetition. Note that for part of the measurement, the MW is turned off, and reference counts are collected, which we can use to normalize the signal counts. When the microwaves are off-resonance, the NV is constantly repumped into the $m_s=0$ state, and also continuously gives off red photons as it is constantly excited into *e* and decays back down into *g*. As the MW frequency approaches resonance with the $m_s=0$ to $m_s=\pm1$ transition at ~2.87 GHz, we will see a decrease in the fluorescence detected by the photodiode as population is driven into the $m_s=\pm1$ states and then subsequently becomes temporarily shelved in *s*.

Application of an external magnetic field will result in Zeeman splitting of the otherwise degenerate $m_s=\pm1$ states, causing the single resonance at ~2.87 GHz to split into multiple resonances. For a single NV, the +1 and -1 states are split, resulting in two resonances, or dips. The size of the separation between the resonances is given by

$$\Delta=2\gamma B_z$$

Here γ is the electron gyromagnetic ratio. Measuring the shift in these dips enables us to measure the magnetic field.

Procedure:

1. Uncomment `nv.do_resonance` and comment out all other routines.
2. In the NV parameters, set the `magnet_angle` to a value of 0.
3. This routine measures the CW ESR at different frequency values. It takes the following parameters:
    a. `nv_sig`: the NV parameters from the first half of this file. You don't have to do anything with this.
    b. `freq_center`: the center frequency for the sweep. A good value to set it to is 2.87 MHz.
    c. `freq_range`: the total range of the frequency sweep. A good value to set it to is 0.2 MHz.
    d. `num_steps`: the number of points to test in the frequency range. A good value for this is 101.
    e. `num_runs`: the number of times the whole measurements will be repeated, which it averages together in the end. A good value for this is 25.
    f. `uwave_power`: the power, in dBm, of the microwave signal coming from the signal generator. A good value is -15.0 dBm.
4. Run the routine.
5. When the measurement is done, there should be two plot windows. The first plots the signal counts with the reference counts, as well as the normalized counts (signal / reference). The second window tries to fit Gaussian curves to the data.
6. If the data does not show clear dips, you may need to increase the `num_runs`.
7. If the routine successfully fits the dips (which it sometimes fails to do), the frequency values of the dip(s) are printed in the console. If it fails to fit the dips, you can estimate their frequency value by eye.
8. Note the value of the frequency dips.
9. Repeat these measurements with at least 6 different values of `magnet_angle` between 0 and 180 degrees.

Analysis:

1. What do you expect to see in ESR if there is only one NV? What about if you have two NVs at the same spot (that are unresolvable)? Consider how many dips in the ESR you expect to see if the magnet is aligned with the NV orientation or perpendicular to the orientation.
1. By plotting the separation between the dips as a function of the magnet angle, we can determine the angle that maximally splits them. Using your preferred software (excel, Python, …) plot the splitting between resonances as a function of the magnet angle. What function describes the data? Why?
2. Using your plotted data, fit the expected function and determine the magnet angle that maximally splits the resonances. This is the magnet angle that best aligns the magnet to the NV axis. Using our single rotational stage, is the magnet guaranteed to be perfectly aligned with the NV axis? Why?
3. In the NV parameters, set the `magnet_angle` to the optimum value you found. **Run one more CW-ESR at this magnet angle.** When it is finished, copy the lower and higher frequency resonance values into the NV parameters `resonance_LOW` and `resonance_HIGH`. What is the splitting from this optimum magnet angle, and what is the magnetic field along the NV axis?
4. The shot-noise limited sensitivity of DC magnetic field measurements can be estimated using the ESR signal from the equation [1]:

$$\delta B_{DC} \cdot \sqrt{T} = \frac{h\,\Delta\nu}{g\mu_B C\sqrt{I_0}},$$

where where T is the measurement time, h is Planck's constant, $\Delta\nu$ is the linewidth of the ESR dip, $g \approx 2$ is the Landé g-factor, μ_B is the Bohr magneton, C is the contrast in the ESR signal, and I_0 is the NV expected count rate (counts per second). This sensitivity is quoted in the units [$T/Hz^{1/2}$]. From your data, what is the DC magnetic field sensitivity?

Experiment 2

Rabi Oscillations

Theory:

Rabi oscillations can be observed with our NV setup. Rabi oscillations or flopping is the cycling of a two-level quantum system when a resonant frequency is applied. In our case the two-level system is $m_s=0$ and either $m_s=+1$ or $m_s=-1$ for a specific NV orientation. We can drive these transitions by setting the frequency to one of the isolated peaks we found with CW-ESR with the magnet angle set to the optimal angle. To see Rabi flopping, we apply this frequency in the form of MW pulses for a range of times.

Now that we have found the resonant frequencies for the NV centers within our diamond, we can apply a MW pulse at varying lengths to drive oscillations between the $m_s=0$ and $m_s=+1$ or $m_s=-1$ states. This is also how we can find the correct pulse duration for a pi/2 pulse and a pi pulse.

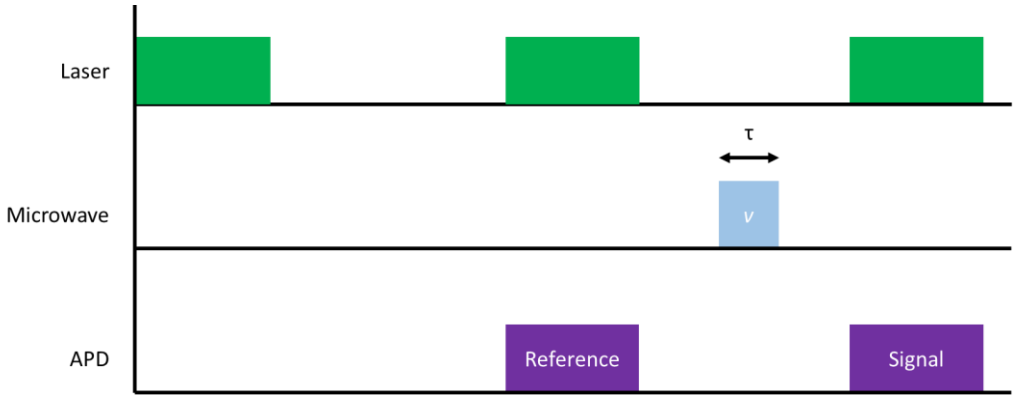

Figure 8: Diagram of the Pulse Sequence for Rabi: An initial polarization laser pulse is applied, followed by a reference laser pulse. The MW pulse is applied for some time T, followed by the signal laser pulse. The length of T is varied each iteration.

Procedure:

1. Uncomment `nv.do_rabi` and comment out all other routines.
2. In the NV parameters, make sure the `magnet_angle` is set to the value you found in the previous experiment, as well as the `resonance_LOW` and `resonance_HIGH`.
3. This routine varies the pulse length of a MW pulse at either the low or high frequency . It takes the following parameters:
    a. `nv_sig`: the NV parameters from the first half of this file. You don't have to do anything with this.
    b. `State.LOW` or `State.HIGH`: tells the routine whether to use the low or high frequency in the NV parameters. You can start with this value as `State.LOW`
    c. `uwave_time_range`: the range of the MW pulse durations it will test, in nanoseconds. A good range is [0, 200] ns.
    d. `num_steps`: the number of points to test in the MW pulse durations range. A good value for this is 51.
    e. `num_reps`: the number of times a single data point is repeated in a measurement. A good value is 10 000.
    f. `num_runs`: the number of times it will repeat the measurement, which it averages together in the end. A good value for this is 15.
4. Run the routine.
5. When the measurement is done, there should be two plot windows. The first plots the signal counts with the reference counts, as well as the normalized counts (signal / reference). The second window fits a decaying cosine to the data.
6. If the data does not show clear oscillations, you may need to increase the `num_runs`.
7. If the routine successfully fits the dips (which it sometimes fails to do), the duration of one full period is printed in the console. If it fails to fit the oscillations, you can estimate the period by eye.
8. Note the value of the full rabi period. Set this value in the NV Parameters for rabi_LOW. Again, this is the full rabi period (a 2-pi pulse)
9. Now change the parameter in the routine to `State.HIGH` to run Rabi on the higher resonance frequency, and record the measured Rabi period.

Analysis:

1. Utilizing the Rabi plots you obtained and your knowledge of Rabi oscillations, what would you estimate the necessary pi/2 and pi pulses to be?
2. What is the change in contrast after one pi-pulse for the low and high resonance? Why is it not 100%?

3. For Rabi and the following spin measurements, the APD readout window is only 350 ns long. For these measurements, we do multiple runs which are then averaged together. Within one run, each data point (one rf frequency or free precession time) is repeated many times and the counts summed together. Based on your data and this information, what is the average number of counts we record during a single 350 ns window? Why can't we increase the readout window to collect more counts?
4. How does the Rabi period depend on the power of the MW pulse? Using the respective `uwave_power` parameter (LOW or HIGH) in the NV parameters (i.e. "`uwave_power_LOW`"), run Rabi with different powers, plot the Rabi period as a function of MW power, and compare to what you expect. Don't go above 15.5. Note that the uwave_power is in dBm. It then goes through a 46dB amplifier.

Experiment 3

Ramsey Sequence

Theory:

The Ramsey pulse sequence can be used to identify the T_2^* coherence time of a quantum sensor or qubit and consists of applying two pi/2 pulses separated by the free precession time. The first pi/2 pulse leaves the NV centers in a superposition of the two spin states. The NV centers are then allowed to precess, accumulating a change in phase. This change in phase is then converted into a change in spin state population through the application of another pi/2 pulse, and is readout optically.

Doing this measurement many times can give a probabilistic representation of the changing phase due to the precession time and eventually, the loss of information due to dephasing. The precession time at which this takes place is known as T_2^*. We apply the pi/2 pulses to the NV centers in our diamond with MW pulses, and vary the precession time gradually in order to determine T_2^*.

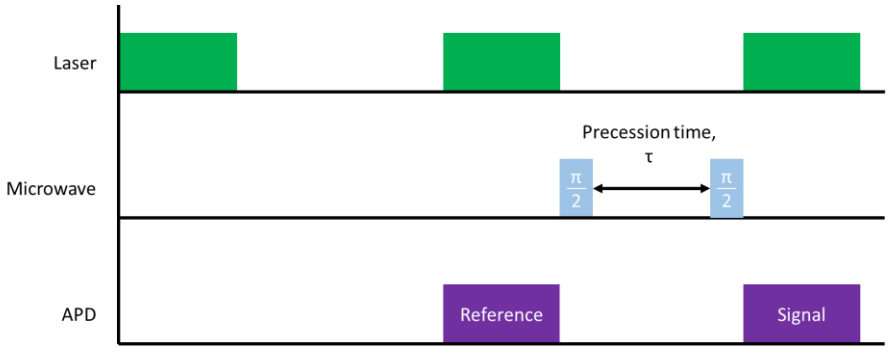

Figure 9: Diagram of Ramsey Pulse Sequence: An initial polarization laser pulse is applied, followed by a reference laser pulse. Then a pi/2 pulse is applied, followed by the precession time. A second pi/2 pulse is applied, followed by the signal laser pulse. The length of the precession time is varied each iteration.

Procedure:

1. Uncomment `nv.do_ramsey` and comment out all other routines.
2. In the NV parameters, make sure the `rabi_LOW` and `rabi_HIGH` are set to the values you found in the previous experiment.
3. This routine varies the precession time between two pi/2-pulses. It takes the following parameters:
    a. `nv_sig`, which has the NV parameters from the first half of this file. You don't have to do anything with this.
    b. `State.LOW` or `State.HIGH`, which tells the routine whether to use the low or high frequency and rabi period. Set this value to whichever resonance has the shorter pi-pulse time.
    c. `precession_time_range`, which defines the range of the precession time durations it will test, in nanoseconds. A good range is [0, 8 000].
    d. `num_steps`: the number of points to test in the precession time range. A good value for this is 101.
    e. `set_detuning`, which offsets the resonance frequency value, in MHz. (see explanation in analysis). A good value is 4 MHz.
    f. `num_reps`: the number of times a single data point is repeated in a measurement. A good value is 10 000.
    g. `num_runs`, which defines the number of times it will repeat the measurement, which it averages together in the end. A good value for this is 50.
4. Run the routine.
5. When the measurement is done, there should be three plot windows. The first plots the signal counts with the reference counts, as well as the normalized counts (signal / reference). The second window plots the fast Fourier transform (FFT) of the normalized data. The program tries to find three peaks in the FFT data (the three hyperfine levels) for three frequency values: ω_1, ω_2, ω_3. In the third window, it plots the sum of three cosine functions each with respective frequencies ω_1, ω_2, ω_3.
6. If the data does not show clear oscillations, you may need to increase the `num_runs`.

Analysis:

1. Based on your graphs, what would you estimate T_2^* to be? How much lower is it than the potential ~2 microseconds?
2. Is there any way to extend the coherence time beyond this?
3. The Ramsey experiment can measure DC or very low (kHz) frequency magnetic fields. The sensitivity of a DC magnetic field measurement from the Ramsey experiment is estimated from the equation [1]:

$$\delta B_{DC} \cdot \sqrt{T} = \frac{\hbar}{g\mu_B C\sqrt{n\ T*_2}},$$

   where T is the measurement time, ħ is the reduced Planck's constant, g ≈ 2 is the Landé g-factor, μ_B is the Bohr magneton, C is the contrast in the ESR signal, n is the number of photons collected during a single readout, and T_2* is the DC coherence time. From your Rasmey data, what is the DC magnetic field sensitivity? How does it compare to the estimate based on the ESR data? If they are significantly different, why?

4. The NV experiences hyperfine level splitting due to the spin 1 nuclear spin of the nitrogen. This means that the single dip you see in the CW-ESR is really made of three dips. When running Ramsey measurement, these three dips will couple to the environment differently, and cause a beating of three frequencies. To better see the effect of all three dips in the Ramsey signal, it's easiest to detune the frequency used so that it is not centered on the middle dip, and why we set the detuning to non-zero.

   As explained above, one of the plots shows the FFT of the data. Using this FFT, what is the hyperfine level splitting of the NV center? Hint, the coupling is best measured when the magnet is maximally aligned with the NV axis, and this isn't the case for all the orientations of the NVs in this setup. You may need to look at other NVs and find ones that are better aligned with the magnet.

Experiment 4

Spin Echo

Theory

The spin echo measurement, just as with the Ramsey measurement, can measure the phase accumulated by the NV from an external field. However, by using a pi pulse in the middle of the precession time of the Ramsey sequency, the Spin Echo sequence measures oscillating (AC) signals by filtering out oscillating signals except those oscillating at the frequency of 2/□.

This can be used for nuclear magnetic resonance measurements on materials placed on the surface of the diamond, but you will use it to measure the signal of the carbon atoms in the diamond. Most of the carbon in diamond (98.9%) is the ^{12}C isotope, which has no nuclear spin. However, the remaining 1.1% is ^{13}C, which has a nuclear spin ½ and can be coherently coupled to the electron spin of the NV. When the electronic spin of the NV is in the m_s=0 state, the nuclear spin of nearby ^{13}C atom is free to precess around the magnetic field; however, when the electronic spin of the NV is in a m_s=+-1 state, it will couple to the nuclear spin of the nearby ^{13}C atom. When in a superposition of m_s=0 and a m_s=+-1 state, the state becomes entangled with the ^{13}C nuclear spin. This resulting phase accumulation rate is dependent on the larmor frequency of the ^{13}C and external magnetic field. Spin echo can be used to detect the larmor frequency of the ^{13}C by sweeping the echo time, □, as well as sweeping the magnetic field strength. Here we will not sweep the magnetic field strength and instead we will use the known Larmor frequency [2] to calculate the magnetic field strength at the NV.

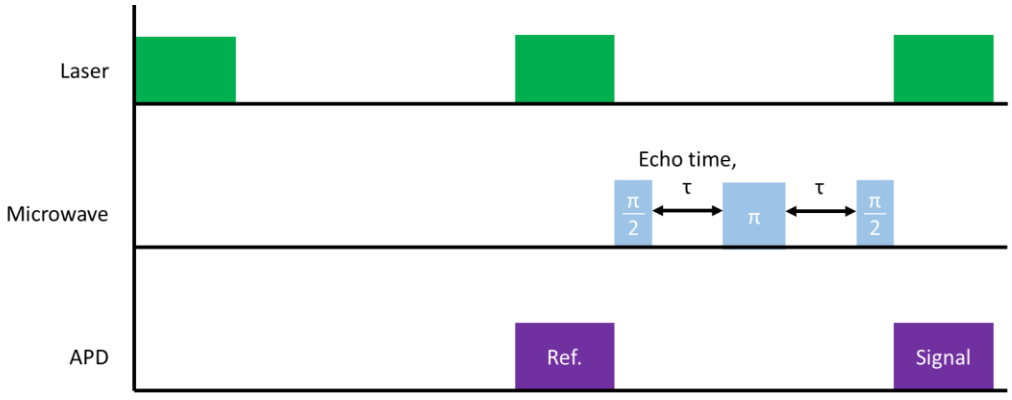

Figure 10: Diagram of Spin Echo Pulse Sequence: An initial polarization laser pulse is applied, followed by a reference laser pulse. Then a pi/2 pulse is applied, followed by an echo

time. A pi pulse is applied, followed by the same duration of the echo time. A second pi/2 pulse is applied, followed by the signal laser pulse. The length of the echo time is varied each iteration.

Procedure:

1. Uncomment `nv.do_spin_echo` and comment out all other routines.
2. This routine varies the echo time, □, in the pulse sequence displayed above. It takes the following parameters:
    a. `nv_sig`, which has the NV parameters from the first half of this file. You don't have to do anything with this.
    b. `State.LOW` or `State.HIGH`, which tells the routine whether to use the low or high frequency and rabi period. Set this value to whichever resonance has the shorter pi-pulse time.
    c. `echo_time_range`, which defines the range of the echo time durations, □, it will test, in nanoseconds. A good range is [0, 150 000].
    d. `num_steps`: the number of points to test in the echo time range. A good value for this is 151 (or 1 point per microsecond).
    e. `num_reps`: the number of times a single data point is repeated in a measurement. A good value is 10 000.
    f. `num_runs`, which defines the number of times it will repeat the measurement, which it averages together in the end. A good value for this is 50.
3. Run the routine.
4. When the measurement is done, there should be two plot windows. The first shows the signal counts with the reference counts, as well as the normalized counts (signal / reference). The second shows a fit to the normalized counts. The fitting function consists of a sum of exponentials of quartics, one for each revival. This function is fitted to the data to extract the revival time: the interval between each revival. The data may appear slightly different in the two pot windows. This is because in the current code one assumes the reference counts is constant and one does not.
5. If the data does not show clear revivals (see [2] for example), you may need to increase the `num_runs`.

Analysis

1. The spin echo measurement measures AC fields, and so the relevant coherence time is T2. With your spin echo data, record the normalized contrast and the echo time value of each of the revival peaks, and using your preferred plotting software, plot the contrast as a function of echo time. What function should be fit to this data? Based on the function you chose, what is the T2 time of the spin echo data?

2. The NV and the spin echo measurement is a useful tool for quantum sensing. To estimate the maximum sensitivity of the NV to measure AC magnetic fields, the following equation is used [3]:

$$\delta B_{AC} \cdot \sqrt{T} = \frac{\hbar}{g\mu_B C\sqrt{n\ T_2}},$$

Where T is the measurement time, ħ is the reduced Planck's constant, g ≈ 2 is the Landé g-factor, μ_B is the Bohr magneton, C is the contrast in the ESR signal, n is the number of photons collected during a single readout, and T_2 is the coherence time. Using the T2 time you estimate from your data, calculate the minimum sensitivity of the magnetic field of your measurements. How does this compare to the DC sensitivity?

3. Finally, calculate the magnitude of the magnetic field at the NV from your spin echo measurement using the known Larmor frequency of the ^{13}C, 1.071 kHz/G [2]. From Experiment 1, you were able to estimate the magnetic field *along the axis* of the NV center. Based on your answers, is the magnet well aligned with your NV center's axis?

[1] L. Rondin et al., "Magnetometry with nitrogen-vacancy defects in diamond" Rep. Prog. Phys. (2014) **77,** 056503

[2] L. Childress et al., "Coherent Dynamics of Coupled Electron and Nuclear Spin Qubits in Diamond" Science (2006) **314**, 5797

[3] J. R. Maze, et al., "Nanoscale magnetic sensing with an individual electronic spin in diamond" Nature (2008) **455**, 644–647