Quantum Magnetometry with NV$^-$ Centers

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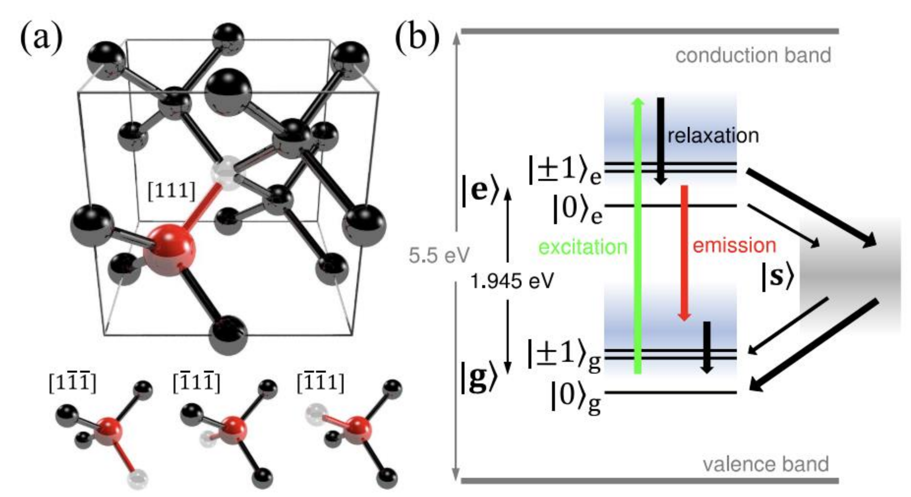
Abstract

Nitrogen vacancy centers provide an accessible environment to observe quantum phenomena because its quantum states are not as sensitive to external factors such as temperature; whereas most quantum systems need to be in cryogenic temperatures to be experimented with. We used the quantum properties of these objects to measure external magnetic fields. To gather the necessary data, we used an optical setup paired with a photoluminescence detection scheme, eventually helping us gain a better understanding of NV-centers and their applications to quantum magnetometry.

Introduction

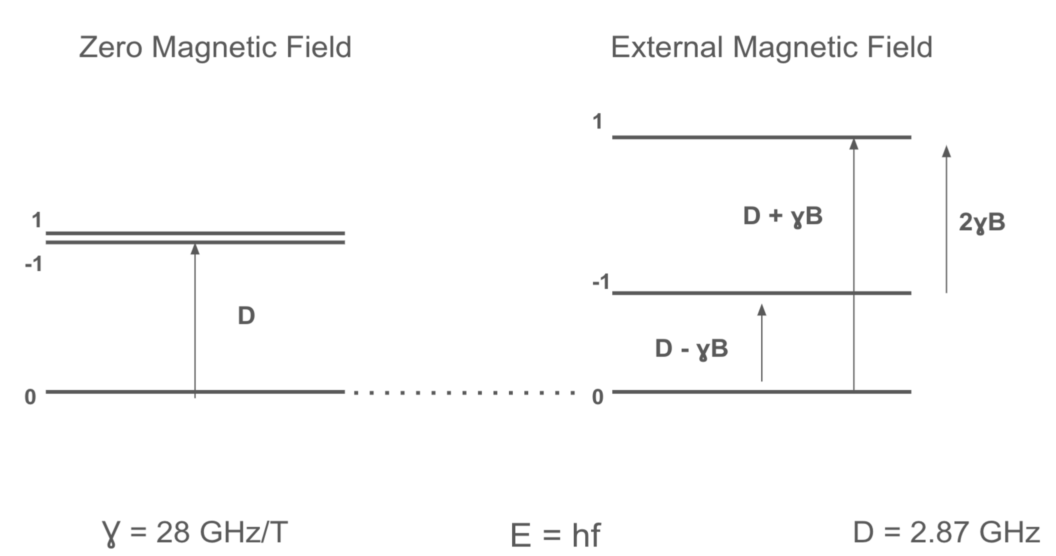
NV-centers are defects in diamond lattices, in which a carbon atom is replaced by nitrogen, creating adjacent vacancies. These vacancies behave like spin-1 particles and have unique quantum properties.



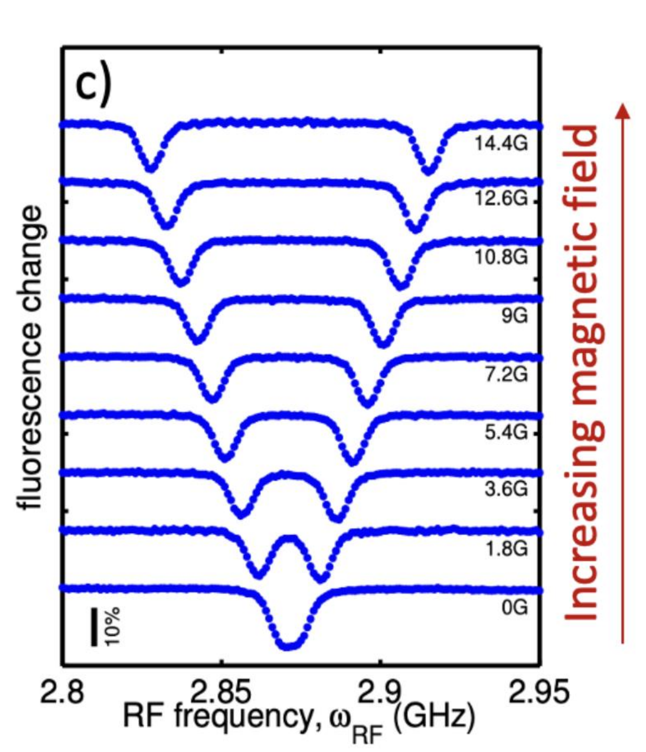
In the presence of a zero magnetic field, the NV spin states are degenerate. However, the energy levels split apart in the presence of a non-zero field. **The Zeeman effect** describes how an external field lifts degeneracy, caused by the magnetic dipole potential of the NV-center. It establishes a mathematical link between the energy splitting in NV-centers and the field strength.

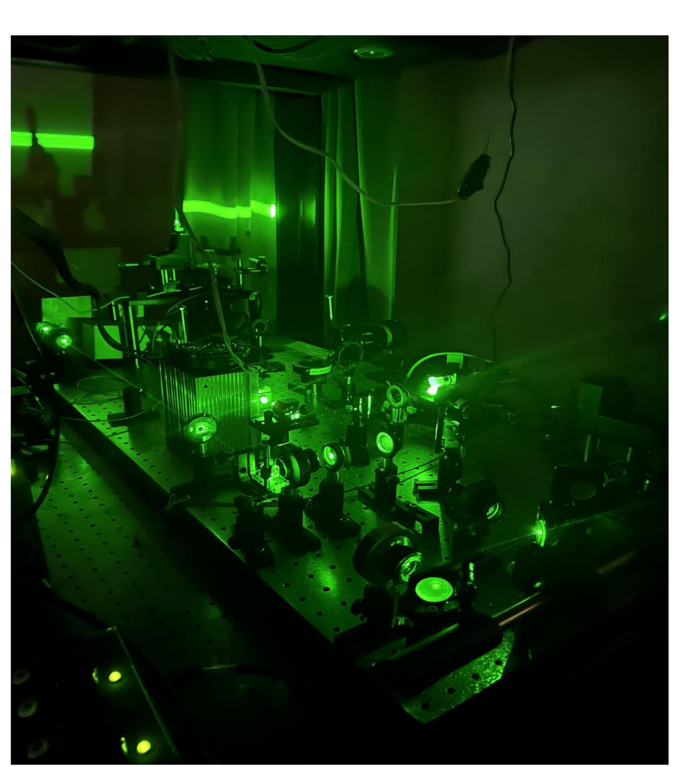
Simplified relation when the magnetic field and NV-axis are parallel:

$$\nu_- = D + \gamma B \qquad \nu_+ = D + \gamma B$$



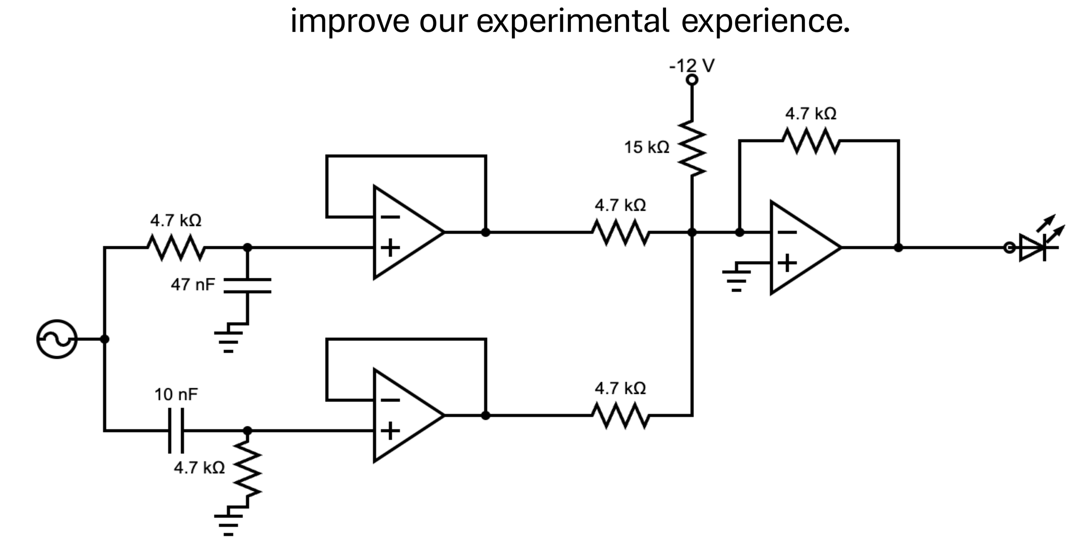
Lastly, **optically detected magnetic resonance (ODMR)** involves inducing electron spin state transitions in the ground energy level of NV-centers using oscillating magnetic fields (microwaves). This shifts the NV-center from the 0 spin-state to the +/- 1 spin-states at resonance. Additionally, a green laser prompts the NV-center's 0 ground state to transition to excited states and then emit light upon returning. Hence, if the NV-center is in the +/-1 ground state and exposed to the laser, it remains unexcited and doesn't emit photons, creating a "dark state". This enables the detection of Zeeman splitting and magnetic fields via the photoluminescence response of NV-centers to sweeping microwave frequencies.

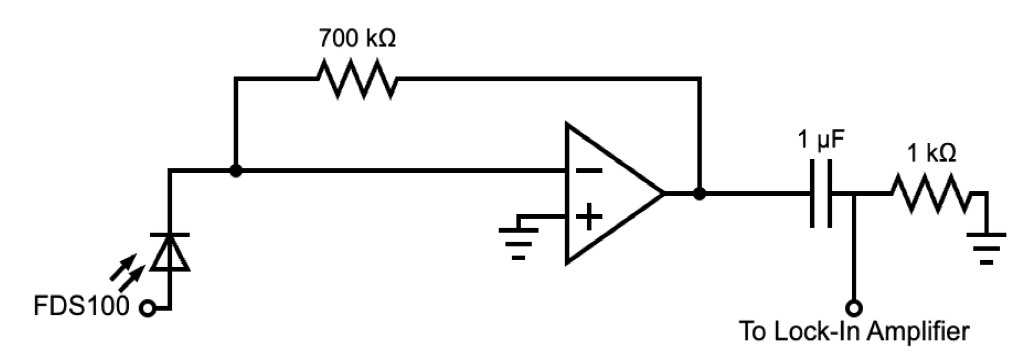




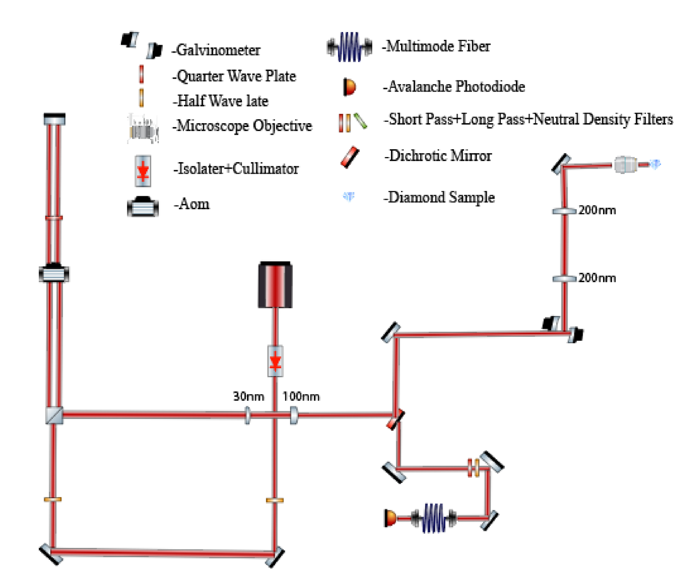
Methods/Results

Before collecting our data with the proper experimental setup, we built a **mock photoluminescence detection circuit**. We simulated the NV-center using a LED fed with current passing through a band stop filter, which attenuates current at a resonance frequency, thus mimicking dips in photoluminescence of NV-centers at resonance. Furthermore, we used a photodiode in a photoconductive circuit paired with a passive low pass filter to collect the photoluminescence coming from the LED, mimicking the experimental setup. Finally, we fed the photon data through a Lock-In Amplifier to clear up any noise and obtain our simulated data. This allowed us to improve our experimental experience.

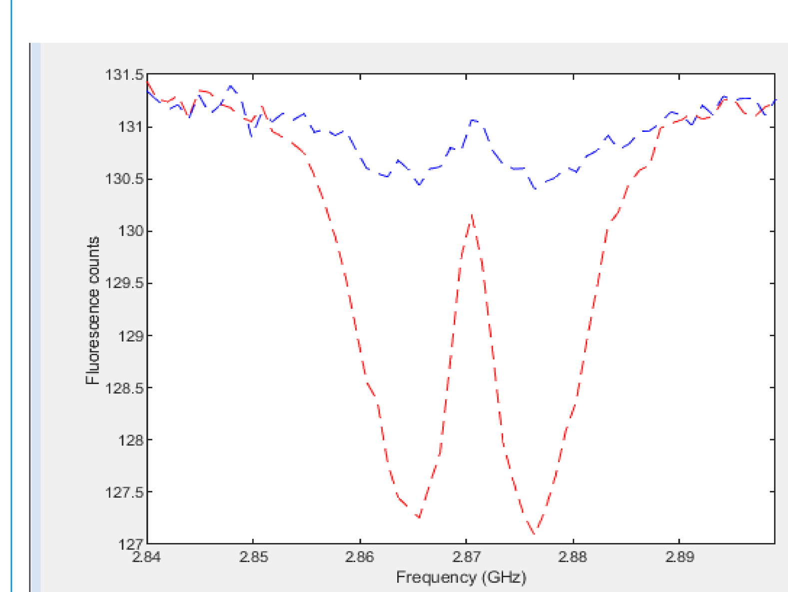




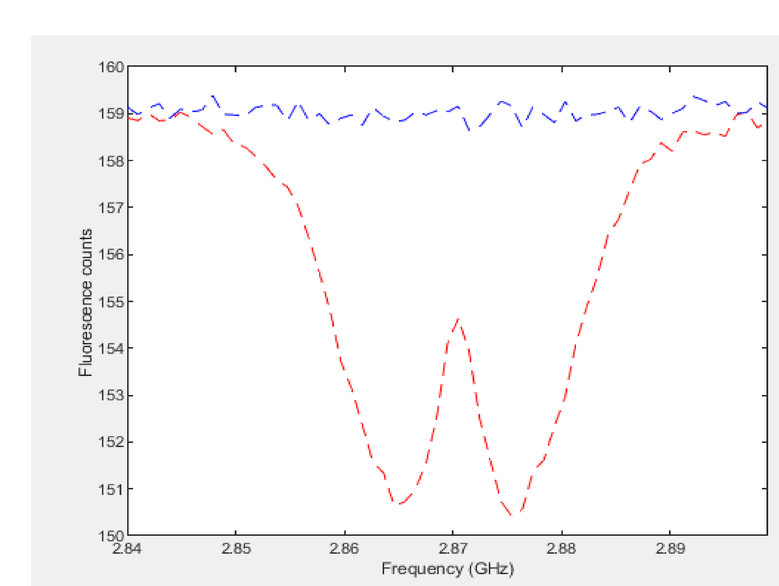
This is the reconstructed Diagram of the experimental setup of the physics 111B NV-Center setup. This display portrays the laser beam path



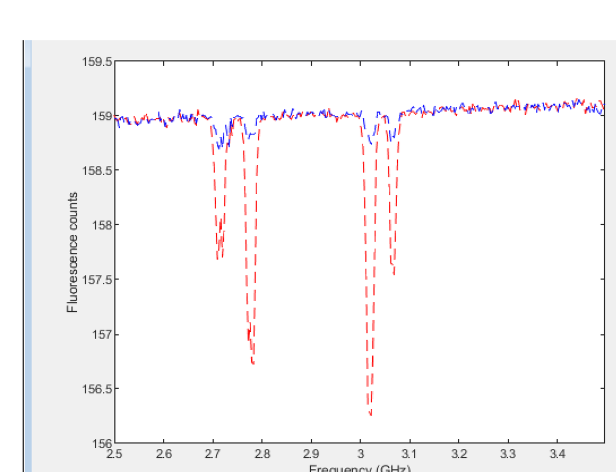
Pump Time Test Graph



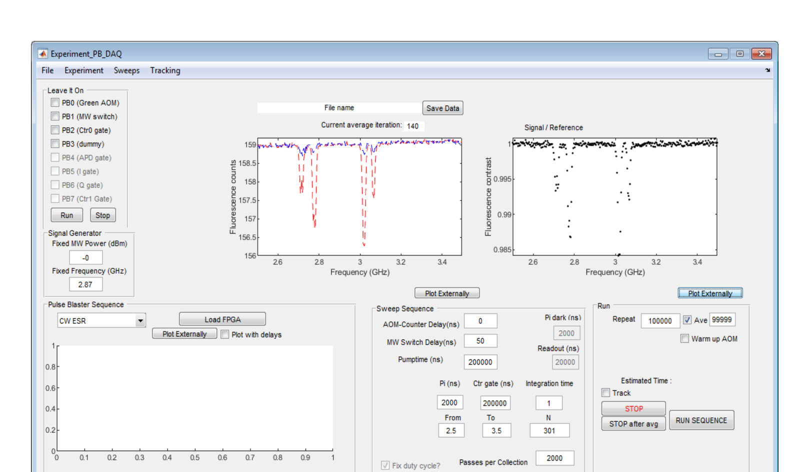
MW Power Graph



ODMR Counts graph



ODMR Settings



Future Work

This project is heavily focused on the simulation of phonon-assisted fluorescence of NV center. For further study of this project, students should aim to gain more precise control and understanding of optic setup along with laser alignment, which are essential for ODMR. Expanding this project could involve investigating applications of phonon-assisted fluorescence in NV centers, such as use in quantum sensing in medical/technical equipment. Integrating NV centers into quantum computing platforms could create hybrid quantum systems with stronger computing capabilities. Overall, extending the project could lead to groundbreaking advancements in both fundamental quantum science and practical quantum technologies.

Conclusion

We produced results from the experimental setup that matched our theories by seeing dips in the optically detected magnetic resonance counts. Our pre-experimental mock photoluminescence detection circuit proved incredibly beneficial for familiarizing ourselves with the Physics 111B NV-Center setup. By simulating NV-Center behavior and employing signal processing techniques, we successfully replicated crucial experimental aspects. This hands-on exercise not only deepened our understanding but also honed our skills in data collection and noise reduction, paving the way for more effective research with NV-centers in the future.

Acknowledgements

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