Measuring magnetic field in materials using NV centers in diamond

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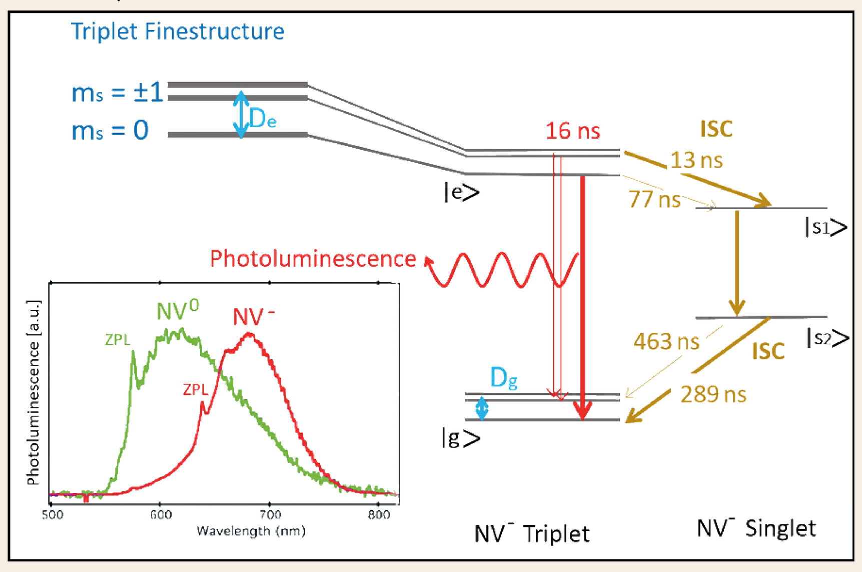
Introduction

- Nitrogen - Vacancy (NV) centers in diamond are defects in the carbon structure of diamond, consisting of a Nitrogen atom and an adjacent Vacancy
- These behave like a spin 1 quantum system, whose energy states can be manipulated using lasers. Allows for quantum detection at room temperature
- The system's photoluminescent response gives informations on the magnetic field surrounding the NV center due to the Zeeman effect

Theory

- Spin 1 ground state : $|m_s = 0\rangle, |m_s = \pm 1\rangle$
- After excitation, $|m_s = 0\rangle$ relaxes via **photoluminescence** at $D/h \approx 2.87$ GHz
- $|m_s = \pm 1\rangle$ excited states relax back to $|m_s = 0\rangle$ through transition states and radiate less
- Zeeman spliting through a static $\vec{B_0}$ field can lift degeneracy between states, resulting in shifted resonance :

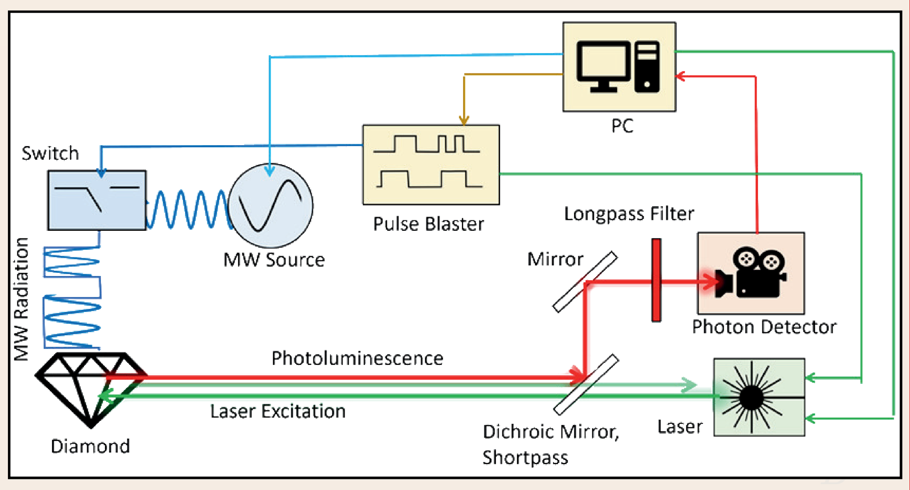
$$\nu = D \pm \gamma_{NV} B_0 \text{ with } \gamma_{NV} = 2.8 \text{ MHz/G, the gyromagnetic ratio}$$



State transitions of the NV center [1]

Experimental setup

- A 517 nm laser excites the NV center in the diamond creating an excited state.
- Shortpass and longpass filters separate laser excitation and photoluminescent (PL) response
- PL signal is recorded by photon detector and sent to PC
- Microwave (MW) frequency can be adjusted to manipulate spin states and find resonance



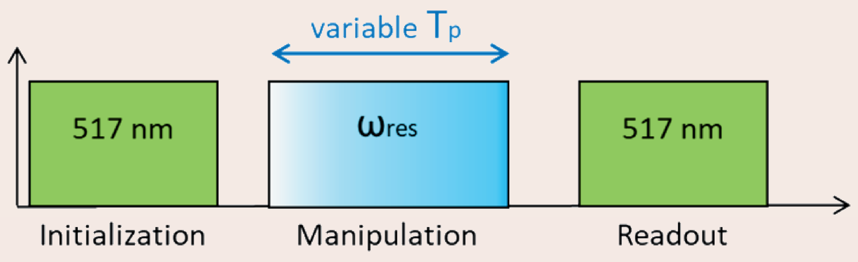
Experimental setup [1]

Rabi sequences

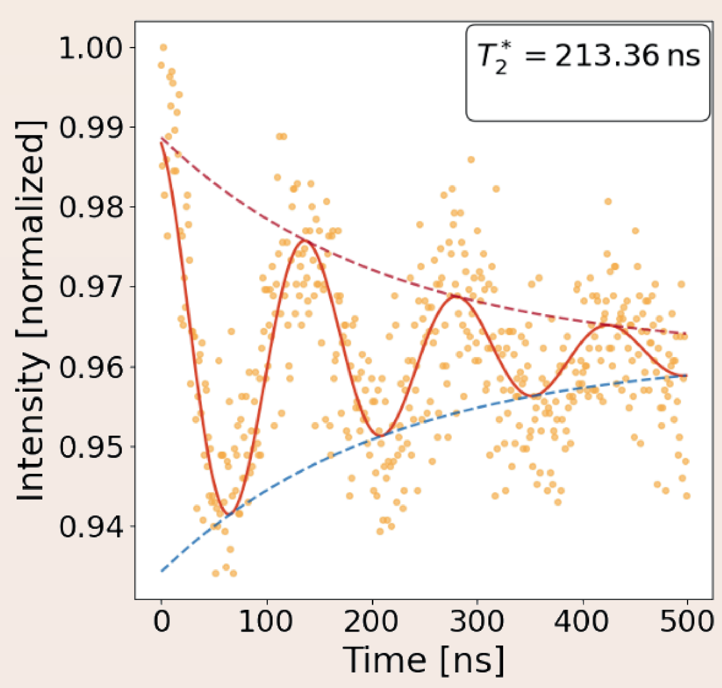
- At MW resonance, spin precesses around the oscillating field
- In the rotating frame, spins precess at frequency $\Omega_R = 2\pi\gamma_{NV} B_0$ alternating between $|m_s = 0\rangle$ and $|m_s = 1\rangle$
- Signal fitted with a decaying cosine

$$I\,(T_p) = I_0 \cos\,(\Omega_R T_p) e^{-(T_p/T_2^*)^*}$$

with T_2^* the free induction decay due to decoherence (magnetic noise)



Steps for single measurement [1]

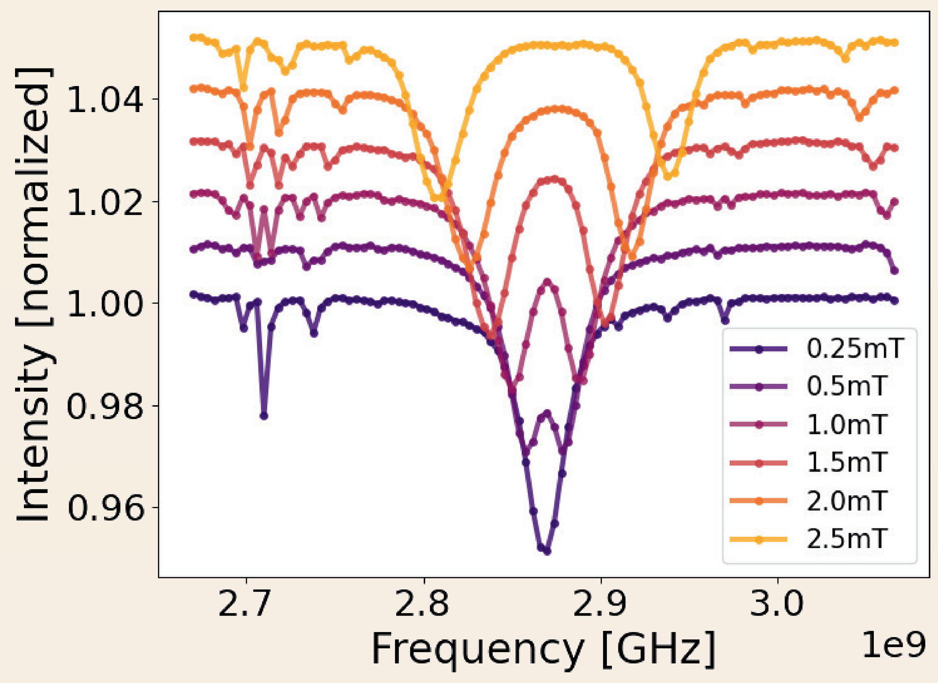


PL intensity as a function of time. With decoherence

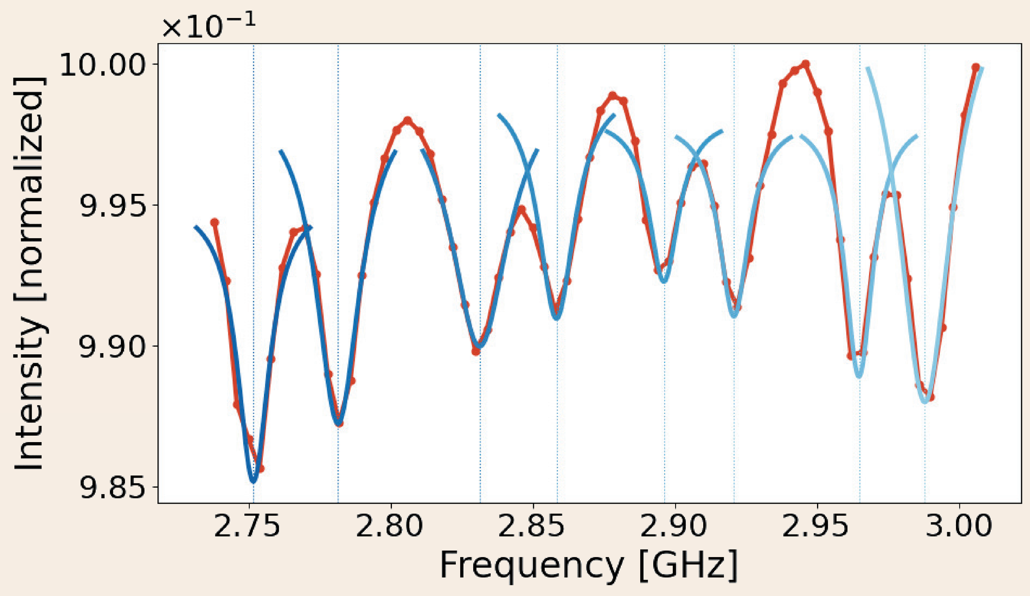
- Measures consist of an initialization at $|m_s = 0\rangle$ through optical pumping, a pulse of variable length and an intensity readout

ODMR

- ODMR (Optically Detected Magnetic Resonance) is used to detect spin transitions between states. When the magnetic field shows resonance with the transition, the system undergoes Rabi oscillations
- Coupling from the $\vec{B}\cdot\vec{S}$ term in Hamiltonian [2] : $|m_s = 0\rangle \leftrightarrow |m_s = \pm 1\rangle$ transitions from $|m_s = 0\rangle$ to $|m_s = \pm 1\rangle$ at MW resonance
- $|m_s = \pm 1\rangle$ emit less photons resulting in a dip at resonance
- Measure of light intensity as a function of MW frequency
- Higher B_0 causes a larger split between $|m_s = 1\rangle$ and $|m_s = -1\rangle$ resonant frequency
- We observe the lift of degeneracy

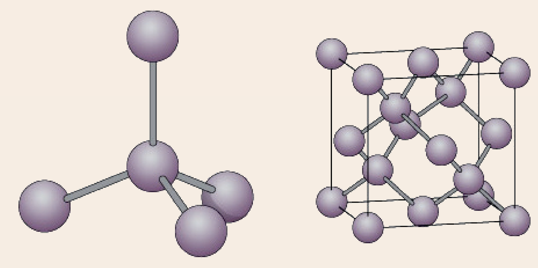


Zeeman splitting of $|m_s = 1\rangle$ and $|m_s = -1\rangle$ frequencies



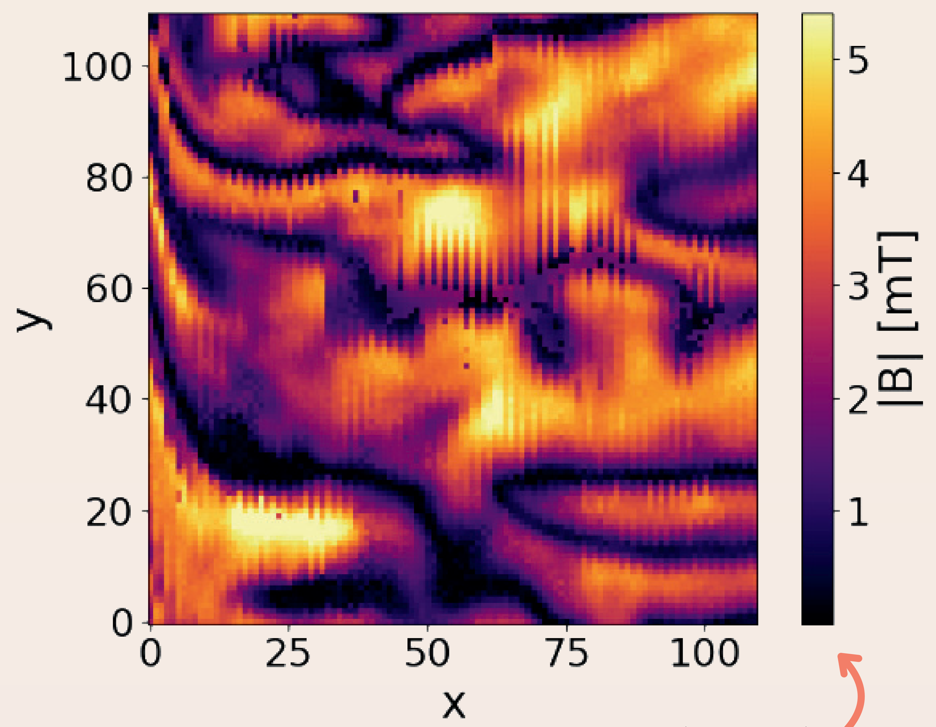
All 4 resonant frequency pairs

- 4 different NV orientations in diamond due to the structure
- 2 resonances per orientation due to $|m_s = \pm 1\rangle$ states


Orientations in diamond / diamond lattice [3]

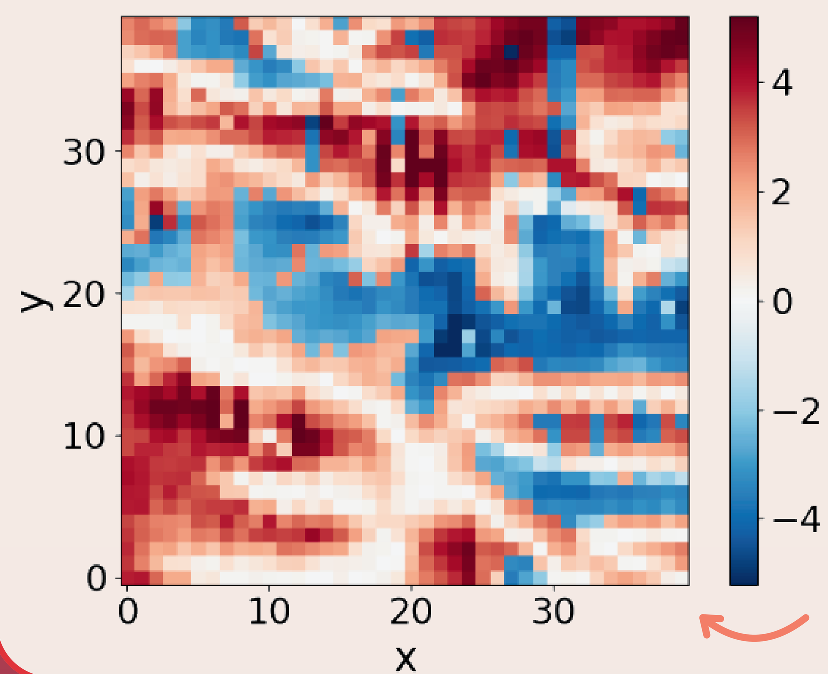
Magnetometry

- A QZabre quantum scanning microscope, is used to measure magnetic fields in material. It combines a NV center probe, laser and MW excitation, fluorescence detection and an AFM distance controller [2].
- The probe is lowered near the material and the ODMR signal is recorded
- A Lorentzian fit interpolates the resonant frequency and $|B_{||}|$ is calculated
- This scan is then repeated at a different location, for a fixed $\vec{B_0}$



2D heatmap of the magnetic response $|B_{(x,y)}|$ of a Galfenol sample, for $B_0 = 12$ mT

- In order to determine the sign of $|B_{||}|$ two measures of the same sample are made for different B_0 magnitude
- Substracting the two results yields a resulting signed field

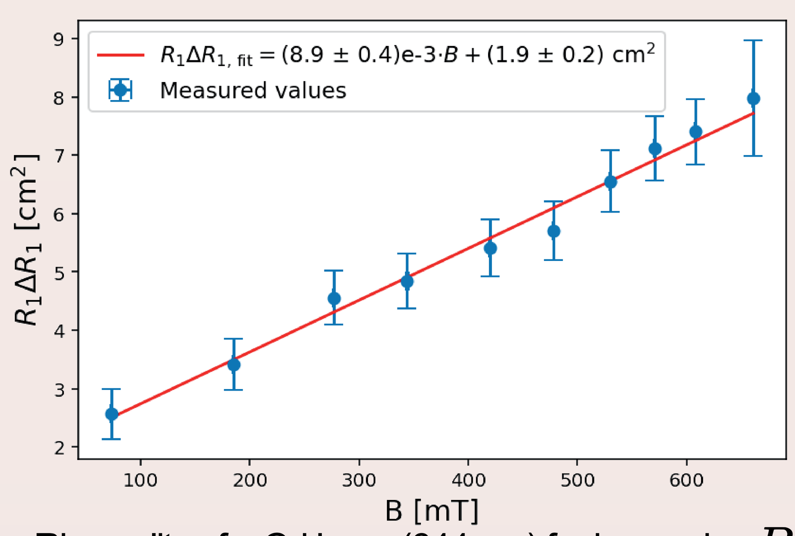


2D heatmap of the signed magnetic response $B_{(x,y)}$ of a Galfenol sample, for $B_0 = 10$ mT and $B_0 = 50$ mT

Zeeman effect

- Fabry-Pérot intereferometer : a sequence of partially reflective parallel plates create beam interferences from which the transmitted light forms concentric rings.
- Zeeman Splitting shifts the rings slighty by ΔR_m which gives : $\Delta\nu = \dfrac{c}{d}\dfrac{R_m \Delta R_m}{f^2\left(\frac{\lambda}{d}\right)}$

  where f and d are geometrical variables.
- Therefore : $R_m \Delta R_m \propto B_0$



Ring splits of a Cd lamp (644 nm) for increasing B_0

Conclusion

- Difference in NV centers spin projection PL emission used to measure magnetic field with great precision
- Transition time between $|m_s = 0\rangle$ and $|m_s = 1\rangle$ and free induction decay using Rabi sequences
- Zeeman spliting between $|m_s = 1\rangle$ and $|m_s = -1\rangle$ gives a way to measure the magnetic field
- Quantum system stable at room temperature

References