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as of 27-Dec-2018

Agency Code:

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Major Goals: The primary goal of the project is the design, acquisition, and installation of a nitrogen-vacancy (NV) defect based scanned probe magnetic resonance instrument. The purpose of the scanned-NV probe is to aid in ultra-sensitive and spatially resolved detection of magnetic resonance. This scanned probe NV capability will allow quantitative and non-invasive measurement and mapping of local magnetic parameters (magnetization, anisotropy, resonant linewidth), and will aid in a more detailed understanding of the NV-ferromagnet coupling interaction central to our proposed approach to biomolecular imaging by means of ferromagnetic amplification.

Accomplishments: We report the installation of a scanned-NV microscopy instrument. The installed apparatus consists of several components.
1. A vibrationally isolated optical table supporting the optical elements for performing confocal fluorescence microscopy measurements on the nanoscale diamond as well as the NV probe structure. Optics include laser, microscope objective, sCMOS camera, and other assorted optics hardware used to build a confocal fluorescence microscope
2. A suspended support structure that positions the NV probe elements, the sample and the objective lens that focuses the incident laser and the fluorescent response of the NV center with respect to the magnetic field. The piezoelectric positioning elements (3-axis coarse-position and fine-scanning stages from Attocube Systems for sample and cantilever positioning and control) and the tuning fork AFM cantilever with single NV tipped diamond cantilever attached (single NV center tipped tuning-fork style cantilevers from Qzabre). This structure is suspended through an opening in a vibrationally isolated optical table.
3. A projected field electromagnet located in the high field region of rotatable electro-magnet that can be easily translated into position. Scanned NV imaging requires the application of magnetic fields ranging from tens of Gauss to ~2 kGauss that can be accurately aligned with the bond-axis of the NV center in the diamond. This is accomplished by combining two electro-magnets acquired from GMW: i) a projected field electromagnet mounted inside ii) the bore of a traditional iron-core electro-magnet. To ensure the feasibility of this configuration, GMW performed magnetic modeling of the field produced by this combination.
4. The signal detection and processing are accomplished by means of a lock-in amplifier from Stanford Research Systems for cantilever measurement and non-contact cantilever feedback. A single photon counting module, acousto-optic modulator and fast timing electronic hardware were acquired for performing time-resolved NV experiments.

Training Opportunities: A graduate student learned to design and assemble the instrument in the course of this project.

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: Brendan McCullian
Person Months Worked: 8.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Final Report for DURIP Project W911NF-16-1-0184:
Ultrasensitive pulsed nuclear spin magnetic resonance spectrometer employing optical detection of nitrogen-vacancy centers in diamond

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We describe design, acquisition, and installation of a nitrogen-vacancy (NV) defect based scanned probe magnetic resonance instrument funded by the ARO DURIP grant W911NF-16-1-0184 covering the period 1 May 2016 to 30 April 2018. The purpose of the scanned-NV probe is to aid in ultra-sensitive and spatially resolved detection of magnetic resonance as funded by the ARO grant W911NF-16-1-0547. The primary results covered by this report are

- Design of the scanned probe NV imaging system
- Acquisition and implementation of the scanning-NV system for spatially resolved magnetic dynamics detection

The scanned-NV system is intended to map the static and dynamic magnetic fields produced by nanoscale magnetic samples. Our work on NV detected magnetic resonance leverages our discovery of non-resonant NV-ferromagnet dynamic coupling, with a goal of driving a ferromagnetic amplification element with target spins for highly sensitive spin imaging. Scanned probe NV capability will allow us to quantitatively and non-invasively measure and map local magnetic parameters (magnetization, anisotropy, resonant linewidth), and will aid in a more detailed understanding of the NV-ferromagnet coupling interaction central to our proposed ferromagnetic amplification scheme.

Introduction

The goals of the research funded under our ARO project are the following:

- Investigation of the NV non-resonant broadband detection of FMR, first demonstrated by our group under ARO funding [1-5]
- Coupling of target spin magnetization to a ferromagnetic amplification element, with eventual readout by NV spins, with the aim of performing sensitive and spatially resolved imaging of target spins

The first goal relies on quantitative measurement and spatial mapping of the non-resonant NV-FMR coupling. Scanned probe positioning of a single NV defect near the ferromagnet will allow us to perform measurements of the FMR generated spin noise at the NV's resonant frequency, allowing for extraction of the coupling strength.[1-3, 6, 7] We note that the NV-NRB coupling is dependent on local magnetic parameters including sample magnetization, ferromagnetic damping parameter and local magnetic anisotropy, in addition to the intrinsic coupling efficiency and profile. The use of the scanned-NV probe to map out the spatial profile of the NV-NRB process will have direct application for our ARO funded project, in that understanding NV-NRB will allow us to place the NV in an optimized spot for ferromagnetic amplifier readout.

The second ARO goal involves challenging device fabrication at the nanoscale for the ferromagnetic amplifier element. Local scanned probe characterization of the ferromagnetic element will help in sample design, measurement of fabrication integrity, and mapping of the external fields from the ferromagnetic element. This information will be crucial for device fabrication with maximum target spin-FM amplifier coupling.

Scanned-NV Probe Design

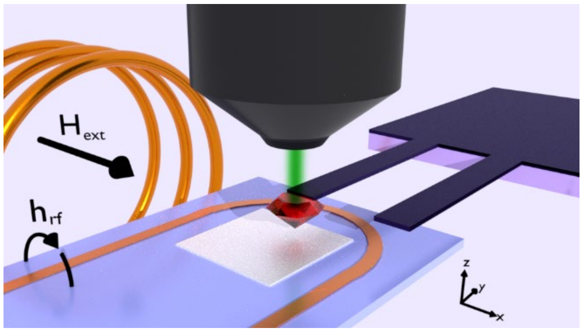

Figure 1 Scanned-NV probe schematic. An NV-tipped cantilever is positioned in the focal spot of a confocal fluorescence microscope. Green light is used to excite the NV center and red fluorescence is used for spin-dependent readout. A proximal element comprised of both magnetic sample and microwave excitation circuit is scanned relative to the NV center in order to perform scanned probe imaging. This scanning element sits inside the bore of an external electromagnet element that provides a static magnetic field used for spectroscopy applications.

The NV defect in diamond has emerged as a leading probe of both static and dynamical magnetic fields.[8, 9] A long spin lifetime, high single defect fluorescence intensity, and the spin-dependent fluorescence allow for sensitive detection of magnetic fields at room temperature and ambient pressure. The proposed uses of our instrument are many, and so the design was intended to be modular in order to meet a wide array of experimental demands.

A few research groups have previously developed custom designed scanned-NV probes, and there is one commercially available system. [10-15] We note a commercial option for acquiring this capability (from Attocube Systems Inc.) costs in excess of $800,000. Following review of the custom-built instruments documented in the literature, we find that this cost is higher than necessary.

A typical scanned-NV setup consists of a few central elements: magnetic field source, NV scanned probe element, confocal fluorescence microscope, and scanned probe hardware. A range of approaches for the instrument have been described in the literature. An example of the variability would be in the approach to applying a vector magnetic field. While permanent magnets on scanning stages are inexpensive and compact, these require extremely precise and challenging alignment in order to change field magnitude while maintaining fixed field orientation multi-axis electromagnets, though more expensive allow straightforward control of field magnitude and orientation. Similarly, the choice of scanned probe element is variable ranging from NV-tipped cantilevers for scanning small samples in the near vicinity of a single NV defect embedded in a macroscopic crystalline diamond substrate.

Following a review of the literature review and an extensive design and critique process, we decided on the following central elements for our scanned-NV system, which we project to yield the best version, at acceptable cost, of the scanned-NV design for our experimental demands:

1. Custom 2-axis vector electromagnet from GMW Associates, allowing for electronic control of magnetic field up to 1 Tesla in-plane and 0.4 Tesla out-of-plane with a rotating base allowing for full vector magnetic field orientation
2. Single NV center tipped tuning-fork style cantilevers from QZabre
3. 3-axis coarse-position and fine-scanning stages from Attocube Systems for sample and cantilever positioning and control
4. Lock-in amplifier from Stanford Research Systems for cantilever measurement and non-contact cantilever feedback
5. Single photon counting module, acousto-optic modulator and fast timing electronic hardware for time-resolved NV experiments
6. Laser, microscope objective, sCMOS camera, and other assorted optics hardware used to build a confocal fluorescence microscope

Scanned-NV Probe Installation

The installed instrument consists of

1. A **vibrationally isolated optical table** supporting the optical elements (described in item 6 above) for performing confocal fluorescence microscopy measurements on the nano-scale diamond. See Figure 2.

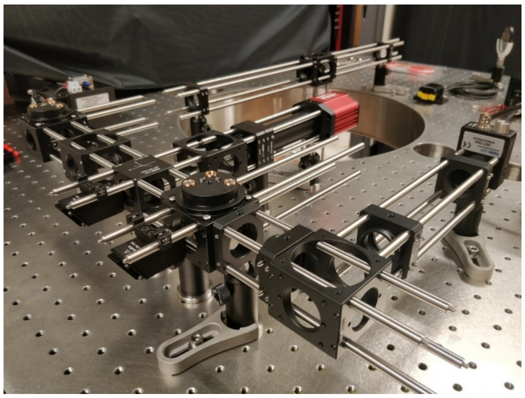

Figure 2. Vibrationally isolated optical table supporting optical elements used for excitation and detection of NV fluorescence. Opening in center provides access to the NV probe elements suspended in the magnetic field

2. A **suspended support structure** that positions the NV probe elements, the sample and the objective lens that focuses the incident laser and the fluorescent response of the NV center with respect to the magnetic field. The piezoelectric positioning elements are shown in Figure 3a and described in item 2 above, and the tuning fork AFM cantilever with single NV tipped diamond cantilever attached, shown in Figures 3b and 4, and described in item 3 above. This structure is suspended through an opening in a vibrationally isolated optical table.

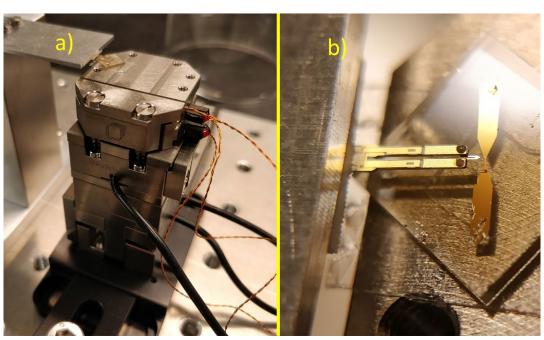

Figure 3. The piezoelectric positioning elements are shown in panel a) and the tuning fork AFM cantilever with single NV tipped diamond cantilever attached is shown in panel b).

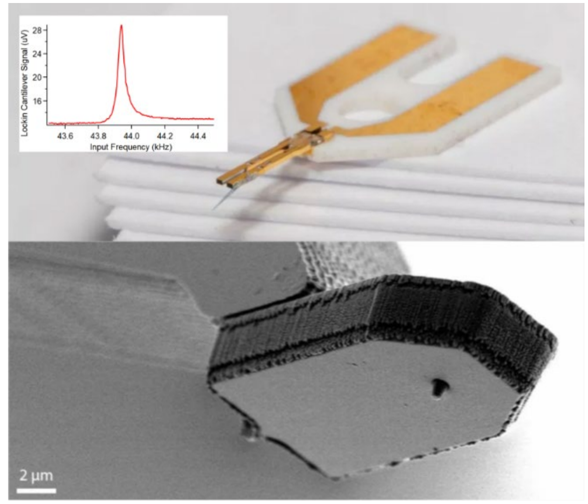

Figure 4 NV tipped cantilever detection. (top) tuning fork style cantilever (inset) lock-in detected of tuning fork cantilever resonance for non-contact scanned probe feedback (bottom) SEM image of diamond cantilever tip with single NV center located 30 nm from the apex of the tip.

3. A **projected field electromagnet** located in the high field region of rotatable electro-magnet that can be easily translated into position. Scanned NV imaging requires the application of magnetic fields ranging from tens of Gauss to ~2 kGauss that can be accurately aligned with the bond-axis of the NV center in the diamond. This is accomplished as shown in Figure 5: we combine two electro-magnets acquired from GMW: i) a projected field electromagnet mounted inside ii) the bore of a

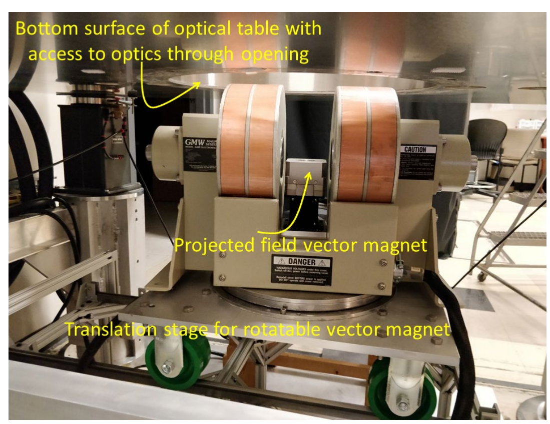

Figure 5. Achieving vector field magnetic field using two electro-magnets: a projected field electromagnet mounted inside the bore of a traditional iron-core electro-magnet.

traditional iron-core electro-magnet. To ensure the feasibility of this configuration, GMW performed magnetic modeling of the field produced by this combination, shown in Figure 6.

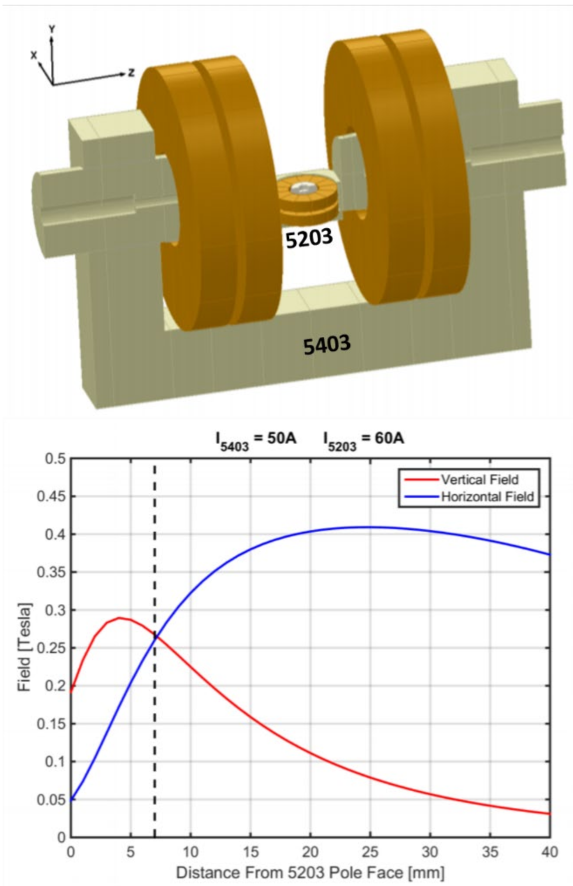

Figure 6. Electromagnet modeling from GMW. (top) Illustration of the primary magnetic elements of the combined 5403 (coil) and 5203 (projected) electromagnet setup. (bottom) Magnetic fields produced by the two magnets, as a function of the distance away from the 5203 magnet pole face, demonstrating that at 7 mm separation the system is capable of producing 2500 Gauss of magnetic field in any orientation in the y-z plane.

4. The **signal detection and processing** are accomplished by means of a lock-in amplifier from Stanford Research Systems for cantilever measurement and non-contact cantilever feedback. A single photon counting module, acousto-optic modulator and fast timing electronic hardware were acquired for performing time-resolved NV experiments.

The constituent elements of the scanned-NV system have been acquired and installed in the lab of P.C. Hammel, located in room 0121 of the Physics Research Building (PRB) on the main campus of the Ohio State University (Columbus, OH). We are continuing the development of the scanned probe electronics of the system and are expecting to perform scanned probe magnetic imaging experiments in the next few months.

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