UROP Report Summer-Fall 2024: Control and Read-Out of Tin-Vacancy Qubits in Diamonds

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Abstract: Our system aims to enable high-precision optical control and readout of tin-vacancy qubits in diamond samples at cryogenic temperatures. It features a MEMS mirror for efficient scanning and an NI DAQ with Qudi for data acquisition. A piezoelectric stage with a custom GUI ensures precise alignment. CAD-designed aluminum components provide stability at sub-Kelvin temperatures. Future work will optimize time-tagging accuracy and real-time cryogenic monitoring. © 2025 The Author(s)

1. Introduction

We are developing an optical setup for controlling and reading out tin-vacancy qubits in diamonds, key components for future quantum networks. The setup uses a cryogenic cooling system and a MEMS mirror for efficient, cost-effective confocal scanning, replacing conventional galvo mirrors to avoid dual-axis scanning aberrations. This enables fast characterization of multiple diamond nanostructures within a single field of view. By driving atomic transitions with diffraction-limited laser beams and using single-photon detection to read out qubits, the system aims to improve control, measurement, and quantum entanglement of tin-vacancy qubits, advancing quantum technologies.

2. Approach

2.1. System Overview

Our system features a confocal microscope scanner integrated into a cryogenic cooling setup. The scanner utilizes a two-dimensional MEMS mirror, enabling single-mirror imaging instead of a traditional two-mirror configuration. A sample is positioned on a piezoelectric-controlled stage within the cryogenic chamber, with a custom-built GUI allowing precise focus adjustments. An NI DAQ captures and processes images of the sample. The following sections detail the development of each system component.

2.2. Confocal Scanner

The optical setup (Fig.A) consists of a collimated Gaussian beam (λ=630[nm]), which is processed through various components, including a long-pass filter, a MEMS mirror, and a beam expander. The beam is magnified by an objective lens before hitting a sample, with reflected light ultimately detected by an avalanche photodiode. The setup enables the scanning of a 658μm x 658μm square area and features single-photon detection through a confocal scanning optics system and a single-photon counting module.

2.3. Scan Processing

To manage the scan data aquisition and display, we have integrated an NI DAQ with Qudi, an open-source Python package for smooth control over various hardware systems. The NI DAQ provides numerous useful features, such as interpreting images presented to our confocal scanner and photon counting. Fig.B demonstrates a calibration measurement on a 3mm x 3mm silicon grid sample. As demonstrated by the image, the system was able to successfully render a 10μm x 10μm portion of the sample. By monitoring large spikes in Qudi's photon counting module, we could reliably bring our sample to focus.

2.4. Time Tagging

Fig.C demonstrates the detection time variation between photon count time gates. Photon presence is simulated through sending a periodic square wave of amplitude 1 and frequency 1MHz. The expected value is 1; however, the Moku Pro has a non-negligible standard deviation we would like to further explore and optimize.

2.5. *CAD Designs*

In designing our confocal microscope, we developed a MEMS mirror holder that securely supports the ThorLabs lens system. It ensures optimal angular positioning, allows ThorLabs metal rods to slide in, and features a through-hole for easy adjustment. A key design choice was aligning the laser beam center with the MEMS mirror center by integrating a pre-built CAD model, ensuring full interaction of incident light with the mirror's neutral and rotated states. We decided to manufacture the holder with aluminum for durability, cost, and ability to withstand sub-Kelvin temperatures. It is demonstrated in Fig.D.

In designing our piezoelectric system, we developed a sample holder to securely maintain the sample while providing little interference with the sample's complex features. It is demonstrated in Fig.E.

2.6. *Piezoelectric Controller*

To control the Piezoelectric stage controller, we utilized an Attocube ANC300 and its accompanying Python library controls. Using PyQt6, a GUI was made to easily manipulate the stage, allowing for precise object calibrations.

3. Results

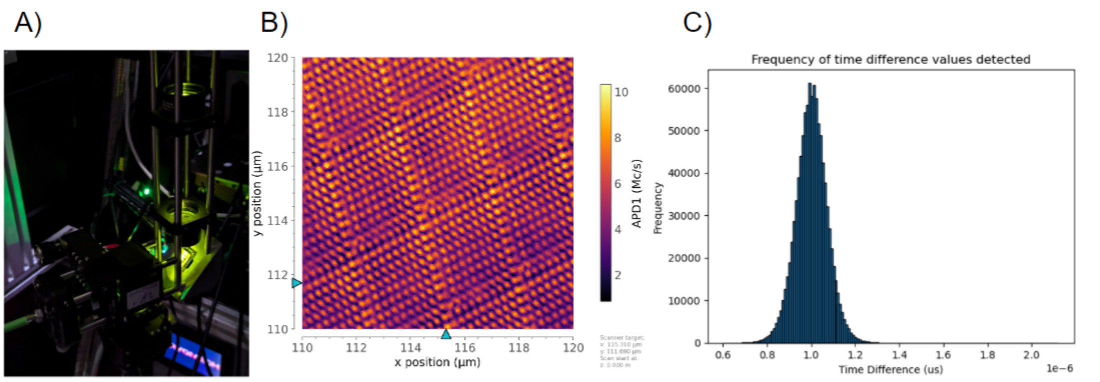

Fig. 1. (A) Full optical setup (B) Sample scan result (C) Frequency of time difference values detected

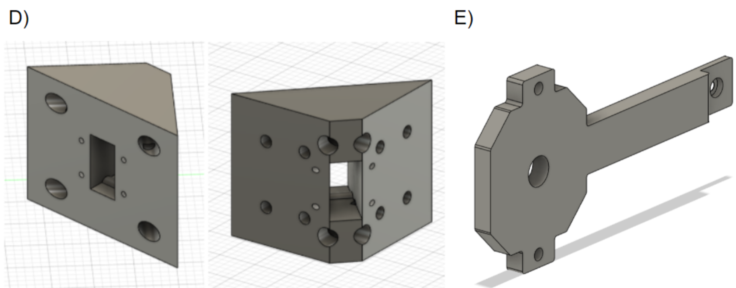

Fig. 2. (D) CAD design for MEMS mirror holder (E) CAD design for sample holder

4. Future Endeavors

We have demonstrated the preliminary functionalities of the confocal microscope, implemented a Python-based open-source control console for quantum emitter cryogenic microscopy, and benchmarked the time-tagging accuracy of an FPGA-based single-photon counting module. Further investigation of the Moku Pro's photon-counting module is required, as the deviations in time difference detection demonstrated earlier could present future measurement issues and uncertainties.

In addition, a projector system has been proposed for real-time monitoring of the cryogenic system while at extreme temperatures. This will make sample alignment significantly faster. To achieve a practical implementation, temperature leakage is a primary concern.