# Enabling photodetection electronics for fluorescent diamond based quantum sensing

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# Contents

# Chapter 1

# Foreword

Chapter 2

# Summary

## Chapter 3

# Abbreviations and terminology

- CW - Constant-Wave
- ECAD - Electronic Computer-Aided Design
- GUI - Graphical User Interface
- MRI - Magnetic Resonance Imaging
- MW - MicroWave
- NV - Nitrogen Vacancy
- ODMR - Optically Detected Magnetic Resonance
- OLIA - Open Lock-In Amplifier
- PCB - Printed Circuit Board

# Chapter 4

# Introduction

This chapter introduces the assignment and some foundational concepts of quantum sensing.

## 4.1 Background

Nitrogen-vacancy (NV) centers [1] are imperfections in the atomic structure of diamonds. The two types of NV centers are NV0 and NV-, as seen in Figure 4.1, but the NV- structure is much more commonly used in quantum applications. These imperfections have the useful property of spin-dependent luminescence. This means that the spin of the NV center affects the frequency of the light emitted by the structure[1]. Using this quality of the NV structure, different environmental metrics (e.g magnetic fields) can be measured.

The Applied Nanotechnology research group is working on a NV-center-based sensor setup. There exist several quantum protocols, but the one this setup needs to support is called Continuous-Wave Optically Detected Magnetic Resonance (CW ODMR). At its core, ODMR is a set of protocols, which can detect magnetic fields based on the fluctuations in the fluorescence of NV centers [3]. CW ODMR in particular involves exposing the NV center to a MicroWave (MW) sweep while illuminating it with a constant light source. This is in contrast with pulsed ODMR techniques, which use different TTL (transistor-transistor logic) pulse schemes [4] to modulate the MW signal and the light source.

Processing data from the setup requires working with weak signals that are hard to distinguish from the environmental noise. While this is a significant problem, it is also a very common one. Because of this, there is already widely-used system used to isolate signals in such cases: the lock-in amplifier.

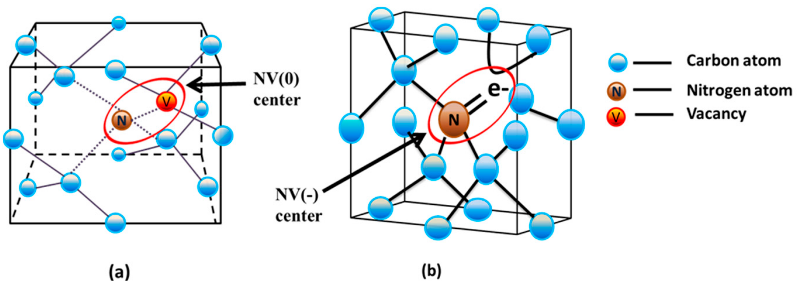


Figure 4.1: NV0 (a) and NV- (b) structures in diamonds (image credit to Haque et al [5])

## 4.2 Purpose of the assignment

Implementing a lock-in amplifier is the main purpose of the assignment. To create a complete solution, there are several different functionalities and systems that need to be developed.

Before doing anything else, the raw sensor data needs to be extracted and then fed to a lock-in amplifier. This should be done in a standardized manner, in order to facilitate testing with different devices. After establishing connection, a control interface needs to be implemented. It needs to

[1] The NV center only emits light after absorbing photons, a phenomenon called photoluminescence [2]

be programmed so that it can control all necessary features of the lock-in amplifier. Following the development of the program, a custom photodetection circuit needs to be designed. The circuit should accommodate the sensors and lock-in amplifier. Lastly, an OLIA[2] circuit needs to be tested and compared to conventional lock-in systems.

## 4.3 Assignment specifications

As already explained, the assignment is quite broad and involves both hardware and software, causing the need for a number of different tools.

Most of the hardware tools are already available at the Applied Nanotechnology lab. The lock-in amplifiers which will be used for the tests are the most important pieces of hardware. Zurich Instruments HF2LI is the benchmark lock-in amplifier. The target amplification is at least 10dB. There are also several different photodetectors available and the one which fits the project best will be picked at a later date. Chapter **??** already discussed the basics of the CW ODMR protocol. In order to get an operational CW ODMR setup, an MW generator and a laser will be used. MW sweeping needs to be done in the range of 2,8 - 2,9 GHz and the lab already has a custom-built MW generator that can output these frequencies. The laser is mostly outside the scope of the assignment, as it is almost entirely optical in nature. Setting it up, together with the NV samples, is up to the client. However, it is important to note that the fluorescence wavelength should be in the range of 637 - 800 nm, as it plays an important part in reading the CW ODMR data.

In terms of software, there is more freedom of choice. Interfacing with the HF2LI is done through proprietary software, but this is the only required program. There are various Electronic Computer-Aided Design (ECAD) software suites that offer the same base functionality. KiCad was selected because the client prefers open-source software. The program for retrieving data from the lock-in amplifiers can be written in both Python and MATLAB. Both languages have good integration with the main lock-in amplifier. They also offer Graphical User Interface (GUI) programming capabilities and are good for scientific computing overall.

## 4.4 Scope of work

### 4.4.1 Project boundaries

The project boundaries were initially based on the assignment form, but were later discussed with the client and refined further.

**Must have**

- Hardware platform for photodetection
- Software for signal processing and visualization

**Should have**

- Tests with different diamond samples

**Could have**

- Tests with different quantum protocols
- OLIA implementation
- Tests comparing OLIA to market solutions

**Will not have**

- Laser as a part of the hardware platform
- Driver upgrade

[2] Open Lock-In Amplifier (OLIA) is an open-source microcontroller-based lock-in amplifier. It uses common components, which makes it easy to build [6]

### 4.4.2 Goals

Based on the MoSCoW priorities from Chapter 4.4.1, a set of goals was created to further specify all items from each prioritization category. Every goal was designed so that its outcome results in a tangible project milestone (e.g. a deliverable).

Goal 1 : Create a hardware setup, which measures and amplifies photodiode signals

Goal 2 : Develop software to process and visualize lock-in amplifier signals

Goal 3 : Compare the performance of different lock-in amplifiers

While these goals are practical, they are still not specific enough. To eliminate the possibility of confusion, a set of tasks were created. All tasks contribute to one of the three goals.

Task 1.1 : Design a photodiode PCB, which can accommodate different lock-in amplifiers

Task 1.2 : Build an operable OLIA

Task 2.1 : Develop software that acquires signals and is then able to visualize them

Task 3.1 : Use key performance metrics to compare the OLIA implementation to market solutions

Task 3.2 : Measure OLIA performance using different diamond samples and quantum protocols

**Task 1.1** involves the design and production of a photodiode PCB. The PCB has to output signals that are not only compatible with lock-in amplifiers that are available on the market, but also with the OLIA. This part of the hardware design has the highest priority, which is why it will be done first.

**Task 1.2** is to build an OLIA amplifier, which can be used at Applied Nanotechnology's laboratory. This will be done with the technical specifications and firmware provided by Harvie and de Mello [6]. The necessity for an OLIA is low, because the Applied Nanotechnology research group already has two lock-in amplifiers.

**Task 2.1** is to write an application in Python or MATLAB. This can be done on a different setup, but ideally it will use the hardware setup from **goal 1**. Because the OLIA project uses open-source firmware that differs from proprietary solutions, there might need to be two separate applications. This task can only be completed once a measurement setup is built, so its execution will follow the first two tasks.

**Task 3.1** requires all previous tasks to be finished. The completed setup needs to be used to measure the performance of lock-in amplifiers available on the market and the OLIA implementation. SNR, bandwidth and stability are the main metrics that need to be compared.

**Task 3.2** is similar to **task 3.1**, but it is a much broader exploration of the performance of the lock-in amplifiers. Using different diamond samples and quantum protocols will show how the amplifier performs and how different conditions affect it. Because the task can be used to verify the setup from **goal 1**, it can also be done before **task 3.1**. Tests with varying diamond samples are more important to the client, which is why they will take precedence over tests with different quantum protocols.

### 4.4.3 Deliverables

The description of the tasks already provided context for the deliverables, but this subsection contains a formalized version of the deliverables.

1. Photodetection PCB
2. OLIA implementation
3. Software application
4. Comparison visualization
5. Technical documentation

The only deliverable, which was not mentioned in Chapter 4.4.2 is the technical documentation. This is because it should contain information about every task.

## 4.5 Methodology

The V-Model methodology was selected, as it is well-suited for low-level projects. Figure 4.2 shows a diagram of the phases of the V-Model. Unlike some software-oriented models, the V-Model is very sequential. This can sometimes be seen as detrimental, but in this case it helps with structuring the project. Another benefit of this model is that there are multiple testing activities, which underpin the quality assurance. A contentious feature of the V-Model is the heavy reliance on the initial requirements. This need for deliberate project requirements can be hard to meet, especially if the client representative is not technically proficient. However, this is not the case in this project. The requirements were extensively discussed with the client representative, based on which the project boundaries in Chapter 4.4.1 were set up.

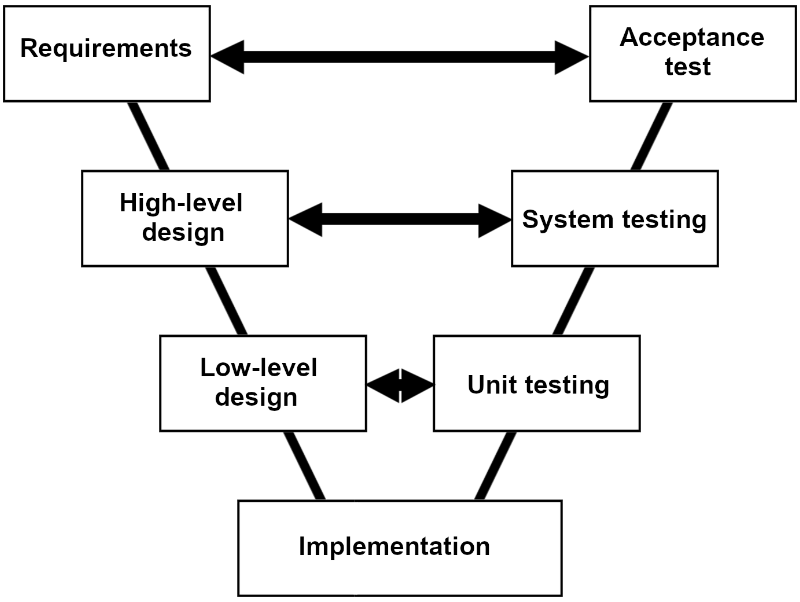


Figure 4.2: V-Model diagram

## 4.6 Report outline

# Chapter 5

# Functional design

## 5.1 Quantum protocols

There are a number of different quantum protocols, which differ in what they can measure, in how precisely they can measure it and in the complexity of the hardware they require to operate. CW ODMR is the main protocol this project is aimed at facilitating. As Saijo et al [7] demonstrate, CW ODMR is relatively simple, while still detecting magnetic field with reasonable sensitivity. Pulsed ODMR does outperform CW ODMR [8], but because of the added complexity working with it is a "Could have" (see Chapter 4.4.1). Before being able to run pulsed ODMR on the setup at the lab, several protocols need to be implemented first [4]. $T_1$ relaxometry, which is one of the fundamentals of Magnetic Resonance Imaging (MRI), should be set up first.

## 5.2 Quantum sensing setup

## 5.3 Photodetection PCB

## 5.4 OLIA implementation

# Chapter 6

# Technical design

## 6.1 Quantum sensing setup

## 6.2 Photodetection PCB

## 6.3 OLIA implementation

# Chapter 7

# Testing results

| Number | Task | Status |
|---|---|---|
| 1.1 | Deploy and configure at least one OpenRemote instance | Completed |
| 1.2 | Establish communication to the OpenRemote instance using the HTTP and MQTT protocols | Completed |
| 2.1 | Simulate IoT devices (smart homes) that send and receive concurrent MQTT data to OpenRemote and measure the latency of the transmissions | Completed |
| 2.2 | Create a physical IoT device setup using a platform like ESP32 or Arduino and recreate the tests from Goal 1.2 | Completed |
| 2.3 | Integrate and test OpenRemote's Prophet project | Not started |
| 2.4 | Test performance and create visualizations | Completed |
| 3.1 | Document technical progress | Completed |
| 3.2 | Reflect on personal and professional development | Completed |
| 3.3 | Communicate project results | Ongoing |

Table 7.1: Goal completion

## 7.1 Test goals and performance metrics

| Metric | API | Unit(s) of measurement | Explanation |
|---|---|---|---|
| Device provisioning latency | HTTP | seconds (s) | Time between creation request and confirmation |
| Message loss percentage | MQTT | percent (%) | Percent of MQTT messages which are lost |
| Resource usage | - | percent (CPU %, RAM %) | CPU and RAM usage when running tests |

Table 7.2: Metrics of the OpenRemote scalability tests

## 7.2 Test setup

## 7.3 Results and discussion

## 7.4 Known limitations

# Chapter 8

# Conclusion

# Chapter 9

# Recommendations

# Appendix A

# Code

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