Guru Nanak Dev University, Amritsar

Six Months Industrial Training Project Report

Second Synopsis

Eighth Semester, Bachelor of Technology, Computer Science and Engineering

Department of CET

Modular ODMR System

A Practical Approach to Quantum Sensing Using Silicon Carbide Defects

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Index

1. Introduction

1.1. Project Progress Overview

The ODMR (Optically Detected Magnetic Resonance) system development has progressed significantly since the first synopsis. The project continues to address the need for a cost-effective, modular quantum sensing system utilizing silicon carbide (SiC) defects. The previous implementation focused primarily on the RF synthesizer development and basic temperature control systems. The current phase has expanded to include advanced signal processing capabilities through the integration of a Red Pitaya board, refinement of the clock generation system using the Si5351 chip, comprehensive GUI development for both hardware components, and acquisition of actual silicon carbide samples with engineered defects.

The project has maintained its focus on creating an accessible quantum sensing platform while advancing toward a complete, functional ODMR system capable of detecting magnetic fields with high sensitivity. The modular approach has enabled incremental development and testing of individual components, leading to a more robust overall system design.

1.2. Current System Implementation

The current implementation represents a significant advancement over the previous phase. The system now incorporates a Red Pitaya board as the core signal processing unit, working in conjunction with an Arduino-controlled Si5351 clock generator for precise frequency control. Both components feature custom-developed GUI interfaces that allow for intuitive operation and real-time parameter adjustment.

The system now includes the following key components:

- Red Pitaya board configured for dual-channel signal acquisition (IN1, IN2) with external triggering capability
- Si5351 clock generator chip integrated with Arduino for precise multi-clock frequency generation
- Python-based GUI for Red Pitaya control and data acquisition
- Separate GUI for Si5351 control allowing individual configuration of clock outputs 1, 2, and 3
- Sweep functionality for frequency scanning
- LabVIEW simulation environment for system validation
- Long-pass optical filter for fluorescence detection
- Silicon carbide samples with engineered defects created through ion implantation

The Python-based GUI for the Red Pitaya board enables data acquisition from both input channels and supports external triggering, which is essential for synchronizing RF excitation with optical detection. The Si5351 control interface allows precise setting of frequencies for each clock output and implements sweep functionality for spectroscopic measurements.

1.3. Achieved Milestones

Since the first synopsis, several significant milestones have been achieved:

1. **Red Pitaya Integration**: Successfully incorporated the Red Pitaya board as the primary signal processing platform, configured for dual-channel acquisition and external triggering.

2. **Si5351 Clock Generator Implementation**: Refined the frequency generation capabilities using the Si5351 chip, now supporting three individual clock outputs with independent frequency control.

3. **Advanced GUI Development**: Created Python-based interfaces for both the Red Pitaya board and Si5351 controller, enabling intuitive control and real-time monitoring of system parameters.

4. **LabVIEW Simulation Environment**: Developed a LabVIEW-based simulation platform to validate system performance and test signal processing algorithms before implementation.

5. **Optical Component Selection**: Acquired and integrated a long-pass filter for fluorescence detection, a critical component for isolating the optical signals from SiC defects.

6. **Sample Acquisition**: Obtained silicon carbide samples with ion-implanted defects suitable for ODMR measurements.

7. **Lock-in Amplifier Development**: Initiated the implementation of a digital lock-in amplifier using the Red Pitaya platform for sensitive signal detection.

These achievements represent substantial progress toward the ultimate goal of creating a functional, cost-effective ODMR system for quantum sensing applications.

2. Components and Relevant Technologies

2.1. Components – Red Pitaya Board

The Red Pitaya board serves as the central signal processing unit in the current ODMR system implementation. This open-source hardware platform combines powerful FPGA capabilities with high-speed analog and digital interfaces, making it ideal for precise measurement applications.

Key specifications of the Red Pitaya board include:

- Xilinx Zynq 7010 SoC (dual-core ARM Cortex-A9 processor + FPGA)
- Dual 125 MS/s 14-bit ADCs for high-resolution signal acquisition
- Dual 125 MS/s 14-bit DACs for signal generation
- 512 MB of RAM for data buffering and processing
- Gigabit Ethernet interface for high-speed data transfer
- Programmable digital I/O for triggering and synchronization
- Linux-based operating system for software flexibility

The Red Pitaya has been configured to serve multiple functions within the ODMR system:

1. **Signal Acquisition**: The dual high-speed ADCs capture fluorescence signals from the photodetector, enabling real-time monitoring of the optical response from SiC defects.
2. **External Triggering**: The programmable digital inputs allow synchronization with the RF excitation, essential for phase-sensitive detection.
3. **Signal Generation**: The DACs can produce reference signals for the lock-in detection process.
4. **Data Processing**: The onboard FPGA and ARM processors handle real-time signal processing tasks, including filtering, averaging, and phase-sensitive detection.

The Python-based GUI developed for the Red Pitaya provides the following functionalities:

- Configuration of input channels (IN1, IN2) for signal acquisition
- External trigger setup and sensitivity adjustment
- Real-time visualization of acquired signals
- Data logging and export capabilities
- Remote control via network connection

The Red Pitaya's capabilities make it particularly suitable for implementing digital lock-in amplification, which is essential for detecting weak fluorescence signals from SiC defects in noisy environments.

2.2. Components – Si5351 Clock Generator

The Si5351 clock generator chip has been implemented as a precision frequency source for the RF excitation required in ODMR measurements. This chip represents a significant improvement over the previously used ADF5351, offering multiple independent outputs with excellent phase noise characteristics.

Key features of the Si5351 implementation include:

- Three independently programmable clock outputs (CLK0, CLK1, CLK2)
- Frequency range from 8 kHz to 160 MHz
- Low phase noise for stable RF excitation
- I²C interface for microcontroller communication
- Programmable output drive strength
- Square wave output suitable for RF amplification

The Si5351 configuration in the current system provides:

- Individual frequency control for all three clock outputs
- Frequency resolution down to Hz level
- Sweep functionality with configurable start/stop frequencies, step size, and dwell time
- Real-time frequency adjustment during experiments
- Phase relationship control between outputs

The ability to generate multiple clock signals simultaneously is particularly valuable for ODMR experiments that require different RF frequencies for manipulating various defect types in SiC. Additionally, the sweep functionality enables spectroscopic scanning of resonance features associated with specific defect centers.

The Si5351 module has been carefully designed with consideration for signal integrity and electromagnetic interference (EMI) mitigation:

- Proper ground planes and power supply decoupling
- RF trace impedance matching
- Shielding to prevent interference
- Clean power supply for low phase noise operation

These design considerations ensure that the clock generator provides stable, precise frequencies required for accurate ODMR measurements.

2.3. Components – Arduino Integration

An Arduino microcontroller serves as the bridge between the host computer and the Si5351 clock generator, handling communication protocols and implementing control algorithms. The Arduino integration provides a flexible and cost-effective solution for precise hardware control.

The Arduino implementation performs the following functions:

- I^2C communication with the Si5351 clock generator
- Serial communication with the host computer
- Register programming for frequency and output configuration
- Sweep implementation with timing control
- Error handling and status reporting
- Firmware update capability via USB

The Arduino firmware includes several key features:

- Command parser for interpreting instructions from the GUI
- Register calculation for precise frequency setting
- Timing control for sweep operations
- Status reporting and error handling
- Calibration routines for frequency accuracy

The integration between Arduino and Si5351 allows for dynamic frequency adjustments during experiments, essential for techniques such as continuous wave ODMR, Rabi oscillation measurements, and pulsed ODMR protocols. The system can transition between frequencies with microsecond precision, enabling time-resolved measurements of quantum phenomena in SiC defects.

The Arduino platform was selected for its reliability, community support, and extensive library ecosystem, which facilitated rapid development and debugging of the control system. The modular approach allows for future expansion of functionality without major redesign of the existing components.

2.4. Components – GUI Development

The graphical user interface (GUI) development has been a significant focus in this phase of the project, resulting in two complementary interfaces: one for controlling the Si5351 clock generator via Arduino, and another for configuring and monitoring the Red Pitaya board.

2.4.1 Si5351 Control GUI

The Python-based GUI for the Si5351 provides the following functionalities:

- Serial port selection and connection management
- Individual frequency setting for all three clock outputs (CLK0, CLK1, CLK2)
- Enable/disable control for each output
- Sweep parameter configuration:
  - Start frequency
  - Stop frequency
  - Step size
  - Dwell time
- Sweep operation controls (start, stop, pause)
- Real-time status monitoring
- Configuration save/load capabilities
- Debug console for monitoring communication

The interface uses PyQt for the graphical elements, providing a responsive and cross-platform experience. Threading is implemented to prevent GUI freezing during serial communication and sweep operations.

2.4.2 Red Pitaya GUI

The Python-based GUI for the Red Pitaya board offers:

- Network connection management
- Input channel configuration:
  - Sampling rate selection
  - Voltage range adjustment
  - Coupling mode (AC/DC)
- Trigger configuration:
  - Source selection (internal, external, software)
  - Level adjustment
  - Edge selection (rising/falling)

- Real-time signal visualization with adjustable time base
- Frequency domain analysis with FFT display
- Data logging controls
- Export options for acquired data (CSV, HDF5)

Both GUIs feature intuitive layouts with logical grouping of related controls, consistent color schemes, and informative tooltips. The interfaces are designed with consideration for workflow efficiency, allowing researchers to focus on experimental parameters rather than hardware details.

The Python implementation leverages several libraries:

- PyQt/PySide for GUI elements
- Pyserial for Arduino communication
- Matplotlib for data visualization
- NumPy for numerical operations
- SciPy for signal processing functions
- Paramiko for SSH communication with Red Pitaya

This software stack ensures robust performance while maintaining cross-platform compatibility, allowing the system to run on Windows, macOS, or Linux operating systems.

2.5. Components – Optical Setup

The optical setup has been enhanced with the addition of a long-pass filter crucial for isolating fluorescence signals from excitation light. This component is essential for detecting the weak optical emissions from SiC defect centers during ODMR measurements.

The current optical setup includes:

- Long-pass filter with cutoff wavelength optimized for SiC defect fluorescence
- Optical mounting hardware for precise alignment
- Photodetector interface compatible with Red Pitaya inputs
- Light-tight enclosure to minimize ambient light interference

The long-pass filter serves a critical function by blocking the excitation laser wavelength while allowing the longer-wavelength fluorescence emission to pass through to the detector. This spectral separation is fundamental to achieving adequate signal-to-noise ratio in ODMR measurements.

Careful consideration has been given to the optical path design:

- Minimizing the number of optical components to reduce losses
- Ensuring proper alignment between excitation source, sample, and detector
- Implementing stable mounting solutions to prevent drift during measurements
- Providing adjustment capabilities for optimizing signal collection

The photodetector output is conditioned to match the input specifications of the Red Pitaya board, ensuring optimal utilization of the ADC dynamic range while preventing signal distortion or clipping. This signal conditioning includes:

- Transimpedance amplification to convert photodiode current to voltage
- Bandwidth limiting to reduce high-frequency noise
- DC offset adjustment to center the signal within the ADC range
- Optional gain stage for weak signal enhancement

The entire optical setup is designed with modularity in mind, allowing for future upgrades or modifications as the project evolves.

2.6. Components – Silicon Carbide Sample Preparation

A significant advancement in this phase of the project has been the acquisition of silicon carbide samples with engineered defects. These samples are essential for demonstrating the ODMR system's capabilities and validating its performance for quantum sensing applications.

The silicon carbide samples have been prepared using ion implantation techniques to create specific defect centers with quantum properties suitable for magnetic sensing. The sample preparation process involved several steps:

- Selection of high-purity silicon carbide wafers
- Ion implantation with specific elements to create vacancy complexes
- Thermal annealing to stabilize defect centers
- Surface preparation for optimal optical access
- Mounting in a holder compatible with the ODMR setup

The defect centers created in these samples exhibit specific optical and spin properties that enable ODMR measurements:

- Optical absorption bands that can be excited with available laser sources
- Fluorescence emission spectra that can be detected through the long-pass filter
- Spin states that can be manipulated using RF fields in the frequency range of the Si5351 generator
- Long coherence times suitable for sensing applications

The samples are mounted in a custom holder that provides:

- Stable positioning within the optical path
- Option for temperature control (important as defect properties can be temperature-dependent)
- Compatibility with RF field application
- Protection from environmental factors that could degrade sample quality

These carefully prepared SiC samples represent a crucial component of the ODMR system, as they provide the quantum system through which magnetic field sensing is achieved.

2.7. Implementation – Signal Processing and Analysis

The signal processing and analysis capabilities of the ODMR system have been significantly enhanced through the integration of the Red Pitaya board and the development of custom software algorithms. These capabilities are essential for extracting meaningful information from the raw fluorescence signals and converting them into magnetic field measurements.

The current signal processing pipeline includes:

- Raw signal acquisition from the photodetector via Red Pitaya inputs
- Digital filtering to remove noise and unwanted frequency components
- Lock-in amplification for phase-sensitive detection
- Averaging to improve signal-to-noise ratio
- Baseline correction and normalization
- Spectral analysis of ODMR resonance features
- Magnetic field calculation from resonance frequency shifts

The digital lock-in amplifier implementation on the Red Pitaya platform provides several advantages:

- Adjustable time constants and filter characteristics
- Precise phase control between reference and signal
- Simultaneous detection of multiple frequency components
- Digital demodulation with minimal drift
- Direct digital output of amplitude and phase information

The LabVIEW simulation environment has been instrumental in developing and testing signal processing algorithms before implementation on the actual hardware. This approach has allowed for:

- Verification of lock-in amplifier performance
- Optimization of filter parameters
- Evaluation of different averaging techniques
- Testing of peak detection and fitting algorithms
- Simulation of various noise scenarios

The analysis software implements several algorithms for processing ODMR spectra:

- Lorentzian and Gaussian peak fitting for resonance characterization
- Calculation of resonance frequencies, linewidths, and amplitudes
- Conversion of frequency shifts to magnetic field values

- Statistical analysis of measurement uncertainty
- Data visualization and export

These signal processing and analysis capabilities transform the raw experimental data into quantitative magnetic field measurements, fulfilling the primary objective of the ODMR system as a quantum sensing platform.

3. ODMR System Integration

3.1. Current Integration Status

The integration of the various components into a cohesive ODMR system represents a significant milestone in the project. The current state of integration includes:

- Functional communication between the host computer and both the Arduino/Si5351 and Red Pitaya subsystems
- Synchronized operation of RF excitation and signal acquisition
- Optical setup with laser excitation, sample positioning, and fluorescence detection
- Signal processing pipeline from raw data to ODMR spectra
- User interfaces for system control and data visualization

The integrated system follows a logical signal flow:

1. The Si5351 generates RF signals at frequencies controlled via the Arduino and GUI
2. These RF signals are applied to the SiC sample, manipulating the spin states of defect centers
3. Laser excitation causes fluorescence emission that depends on the spin state
4. The fluorescence is filtered and detected by the photodetector
5. The Red Pitaya acquires and processes the detector signal
6. The lock-in amplifier extracts the relevant signal components
7. The processed data is displayed and analyzed via the GUI

This integration has been achieved while maintaining the modular architecture of the system, allowing individual components to be tested, modified, or upgraded independently.

3.2. Lock-in Amplifier Implementation

The development of a digital lock-in amplifier using the Red Pitaya platform is currently in progress and represents a critical component for achieving high sensitivity in ODMR measurements. The lock-in amplifier enables detection of small fluorescence changes in the presence of noise by performing phase-sensitive detection.

The lock-in amplifier implementation includes:

- Reference signal generation synchronized with RF modulation
- Analog-to-digital conversion of the photodetector signal
- Digital multiplication of the signal with reference (phase-sensitive detection)
- Low-pass filtering with configurable time constant
- Quadrature detection for phase-independent signal recovery

- Output of amplitude and phase information to the host computer

The current implementation utilizes the FPGA capabilities of the Red Pitaya to perform these operations in real-time with minimal latency. The FPGA-based approach provides several advantages:

- High processing speed for real-time operation
- Precise timing control for synchronization
- Dedicated hardware for critical signal processing tasks
- Reliable performance independent of host computer load

The lock-in amplifier supports various detection modes:

- Continuous wave detection with constant RF frequency
- Frequency sweep mode for spectral acquisition
- Pulsed mode for time-resolved measurements
- Dual-phase detection for complete signal recovery

The performance of the lock-in amplifier is critical for the overall sensitivity of the ODMR system, as it determines the smallest detectable fluorescence change and, consequently, the minimum detectable magnetic field.

3.3. Fluorescence Detection System

The fluorescence detection system has been implemented to capture the optical signals from SiC defects during ODMR measurements. This system includes:

- Photodetector with appropriate spectral response
- Long-pass filter for separating fluorescence from excitation light
- Signal conditioning electronics
- Interface to the Red Pitaya analog inputs

The detection system is designed to maximize sensitivity while minimizing noise sources:

- Ambient light isolation through physical enclosures
- Optical filtering to reject scattered excitation light
- Electronic filtering to suppress noise outside the signal bandwidth
- Proper grounding and shielding to minimize electromagnetic interference

The photodetector signal is conditioned to match the input specifications of the Red Pitaya ADC, ensuring optimal signal-to-noise ratio and dynamic range utilization. This conditioning includes:

- Amplification to utilize the full ADC range

- Bandwidth limiting to reduce noise
- DC offset adjustment
- Protection circuitry to prevent damage from transients

The fluorescence detection system operates in conjunction with the lock-in amplifier to extract the weak ODMR signals from background noise, enabling sensitive detection of magnetic field effects on the SiC defect centers.

4. Next Steps

The project has made significant progress in developing the core components of the ODMR system. The following steps are planned to complete the system development and demonstrate its capabilities for quantum sensing applications:

1. **Complete Lock-in Amplifier Implementation**
   - Finalize FPGA code for the Red Pitaya
   - Implement user interface for lock-in parameters
   - Calibrate and characterize performance
2. **Optimize Optical Setup**
   - Improve laser focusing and alignment
   - Enhance fluorescence collection efficiency
   - Characterize optical stability and signal-to-noise ratio
3. **ODMR Spectrum Acquisition**
   - Perform initial ODMR measurements on SiC samples
   - Identify resonance features associated with specific defect centers
   - Optimize measurement parameters for best signal quality
4. **Magnetic Field Sensing Demonstration**
   - Apply controlled magnetic fields to the sample
   - Measure resonance frequency shifts
   - Calibrate field sensitivity and resolution
   - Characterize system performance metrics
5. **System Documentation and Refinement**
   - Comprehensive documentation of all components
   - Development of user manuals and protocols
   - Identification of areas for further improvement
6. **Final Testing and Validation**
   - Rigorous testing under various conditions
   - Comparison with theoretical predictions
   - Assessment of system limitations
   - Demonstration of practical sensing applications

The completion of these steps will result in a fully functional ODMR system capable of detecting magnetic fields using silicon carbide defects, fulfilling the primary objective of this project. The modular design approach adopted throughout the development process will allow for future enhancements and adaptations to specific application requirements.

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