Guru Nanak Dev University, Amritsar

Six Months Industrial Training Project Report

First 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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1. Introduction

1.1. Problem Statement

Quantum sensing has emerged as a revolutionary technology with applications ranging from medical diagnostics to geology and navigation. Among quantum sensors, Optically Detected Magnetic Resonance (**ODMR**) systems stand out for their ability to measure magnetic fields with high spatial resolution under ambient conditions. However, conventional ODMR systems are often prohibitively expensive, relying on specialized laboratory equipment that costs tens of thousands of dollars. Additionally, these systems typically require extensive technical expertise to operate and maintain, limiting their accessibility to specialized research institutions.

The project addresses the need for a cost-effective, modular ODMR system that can detect magnetic fields using **silicon carbide** (**SiC**) defects. By leveraging open-source hardware platforms and developing custom instrumentation, this project aims to democratize access to quantum sensing technology and enable practical applications of ODMR in educational settings and emerging industrial applications.

1.2. Project Description

The project "ODMR System" is a solution for the above problem statement. Currently, it uses a custom-built RF synthesizer based on **Arduino** and the **ADF5351** chip by **Analog Devices** to generate precise radio frequency signals necessary for manipulating quantum states in silicon carbide defects. The system employs a custom power supply with temperature control system utilizing a computer **SMPS** and **Peltier module** for stable laser operation, and a **Python-based graphical user interface** (**GUI**) for RF synthesizer control.

The project utilizes embedded systems programming, signal processing, instrumentation engineering, and software development technologies. The specific details regarding the same will be mentioned in the subsequent sections.

The **Arduino-based RF synthesizer** provides precise frequency control in the range necessary for ODMR measurements (typically MHz to GHz range). The power supply and temperature control system utilizing a **Peltier module** ensures stable operation of the laser diode, which will be critical for exciting the silicon carbide defects in future implementations. These components are controlled through a custom **Python GUI** that provides real-time control and visualization of the RF synthesizer operation.

Future implementations will include a **Lock-in Amplifier** using the **Red Pitaya** platform for detecting small signals in noisy environments, integration with an optical setup, and development of signal processing algorithms for analyzing ODMR spectra.

1.3. Tasks, Objectives and Challenges

The project requires certain tasks to be completed for success. Crucial tasks include developing the hardware and software components, testing extensively for issues, debugging and resolving those issues, calibrating the system, ensuring integration between components, and documenting the system architecture and performance.

The tasks completed so far include:

- Design and implementation of the **RF synthesizer** using **Arduino** and **ADF5351**
- Development of a **Python GUI** for controlling the RF synthesizer
- Construction of a custom power supply using computer **SMPS**
- Implementation of temperature control for laser diode using a **Peltier module** and heat sink

The objectives of the project are as follows, in no particular order of precedence:

- Creating an ODMR system capable of detecting magnetic fields using **silicon carbide defects** with a reasonable degree of sensitivity and accuracy
- Ensuring that overall processing and display is done within a reasonable time frame
- Preparing the system for possible irregularities and unconventional inputs or environmental conditions
- Elimination of all major bugs and issues that may result in system failure
- Ensuring that users enjoy a hassle-free experience when interacting with the overall system
- Achieving a significant cost reduction compared to commercial ODMR systems

However, the project must consider possible challenges, obstacles, and limitations:

- **Signal-to-noise ratio** is perhaps the most essential consideration, and thus poses the greatest challenge
- **Temperature stability** affects both the laser diode performance and the quantum properties of the silicon carbide defects
- **RF interference** may affect the measurements, requiring careful shielding and grounding practices
- **Power supply stability** is critical for both the laser diode and the detection electronics

It should be noted that at the current juncture, these broad concerns can be taken as overarching issues that must be considered. As the project progresses, many of the above concerns may be obviated, and new issues may emerge.

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2. Components and Relevant Technologies

2.1. Components – RF Synthesizer

The **RF synthesizer** is a crucial component of the ODMR system as it generates the radio frequency signals necessary to manipulate the quantum states of the silicon carbide defects. The project employs a custom-built RF synthesizer based on **Arduino** and the **ADF5351** chip by **Analog Devices**.

The **ADF5351** is a wideband phase-locked loop (**PLL**) frequency synthesizer capable of generating RF signals up to 4 GHz. The key features of this chip that make it suitable for ODMR applications include:

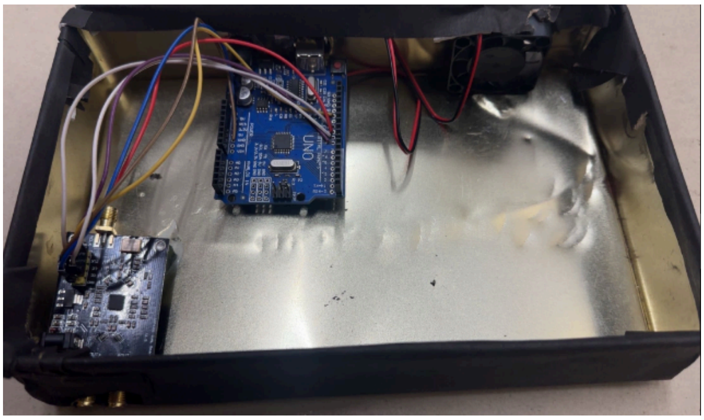
- Wide frequency range (35 MHz to 4.4 GHz)
- Low phase noise performance
- Multiple independent outputs
- Programmable output power levels
- Frequency and phase modulation capabilities

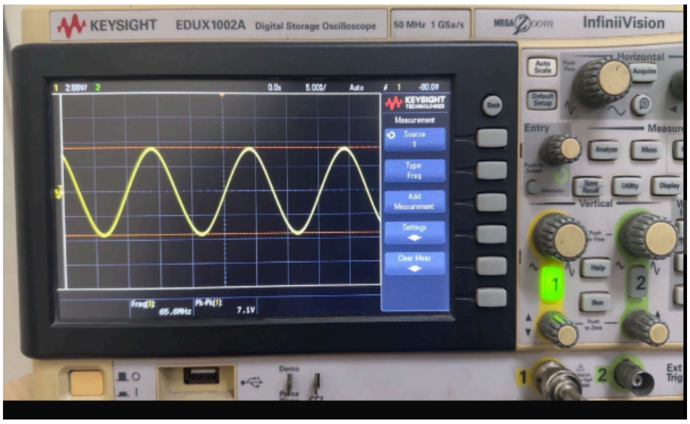
The **Arduino** microcontroller serves as the control interface for the ADF5351, handling the following functions:

- **Serial communication** with the host computer (GUI)
- **I2C communication** with the ADF5351
- Register configuration for frequency, phase, and power settings
- Implementation of sweep and modulation modes
- Error handling and status reporting

The RF synthesizer design includes considerations for power integrity, signal integrity, and electromagnetic interference (**EMI**). These considerations are essential for achieving the clean, stable RF signals required for precise ODMR measurements. The design incorporates:

- Careful PCB layout with proper ground planes
- Filtering of power supplies
- Shielding of sensitive components
- Impedance matching for RF signal paths





The firmware for the **Arduino** controller implements a command protocol that allows the GUI to control various parameters of the RF output, including:

- Frequency setting with sub-Hz resolution
- Output power level control
- **Sweep mode** configuration (start/stop frequencies, step size, dwell time)
- System status monitoring and reporting

Performance metrics for the RF synthesizer include frequency accuracy, phase noise, spurious emission levels, and settling time. These metrics are critical for the overall system performance and are evaluated through rigorous testing and calibration procedures.

2.2. Components – GUI Development

The **Graphical User Interface** (**GUI**) serves as the control point for the RF synthesizer in the ODMR system, allowing users to configure parameters and monitor operation. The GUI is developed in **Python**, leveraging its extensive libraries for scientific computing and visualization.

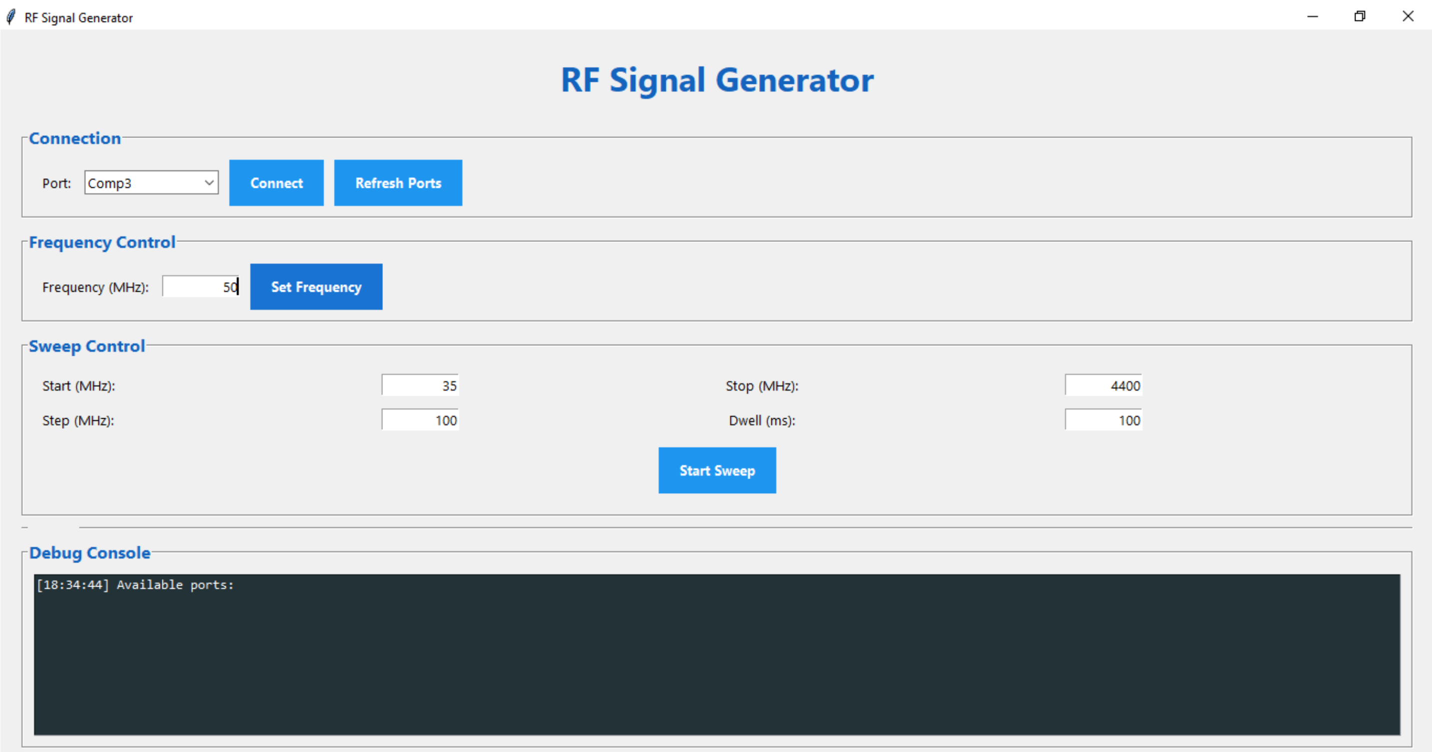
Python was chosen as the development language due to its:

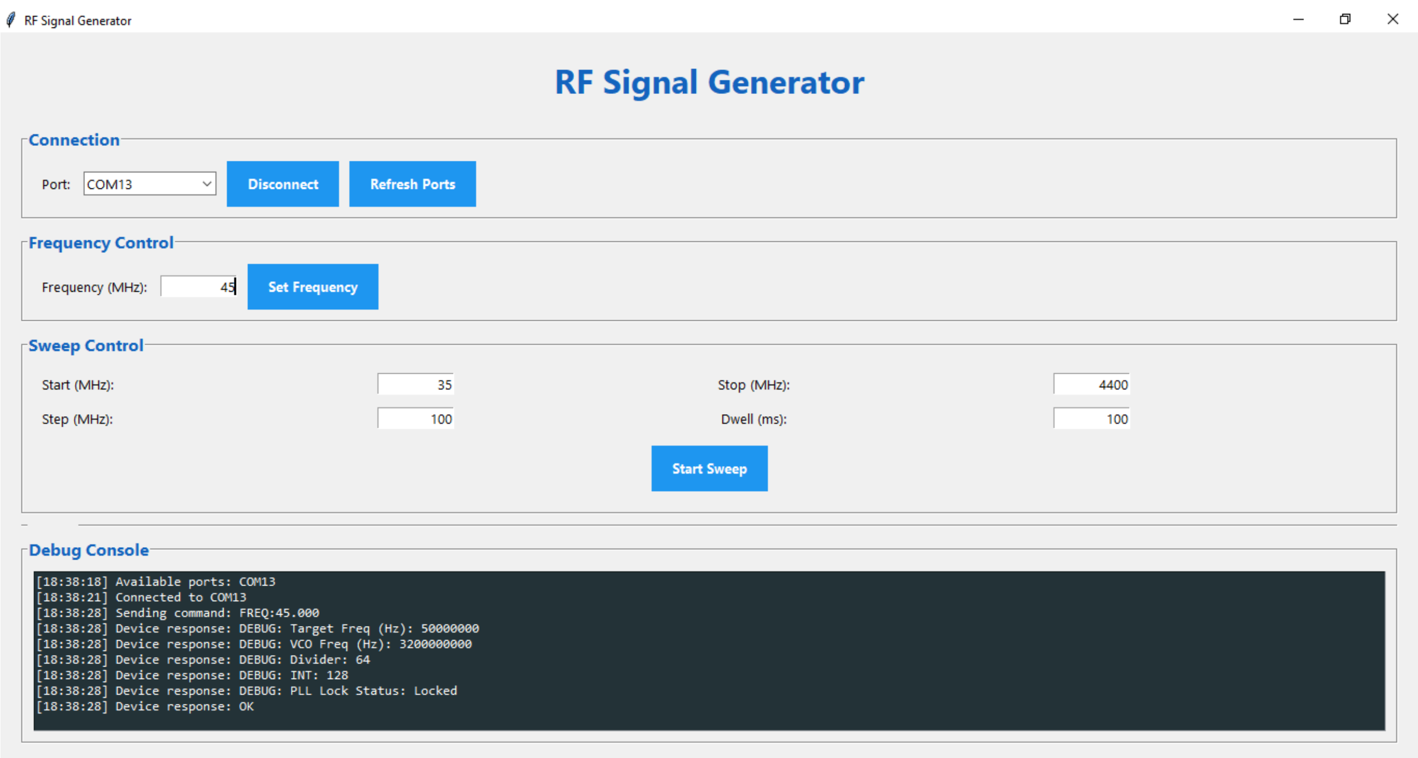
- Cross-platform compatibility
- Rich ecosystem of scientific and data analysis libraries

- Object-oriented programming capabilities
- Ease of integration with hardware interfaces
- Rapid development cycle

The current GUI provides the following functionalities:

- Setting RF frequency parameters
- Port selection for connection to the Arduino
- Connect/disconnect controls
- Configuration of sweep parameters including **dwell time** and step size
- Sweep operation control
- Debug console for monitoring communication with the RF synthesizer





The GUI communicates with the hardware components through **serial communication** with the Arduino-based RF synthesizer. It provides real-time feedback on the status of the RF synthesizer and displays error messages when issues arise.

The interface is designed with user experience in mind, providing intuitive controls, helpful tooltips, and clear feedback on system status and operation progress. The debug console at the bottom of the GUI allows users to monitor the communication between the GUI and the Arduino, helping with troubleshooting and system verification.

2.3. Components – Laser and Temperature Control

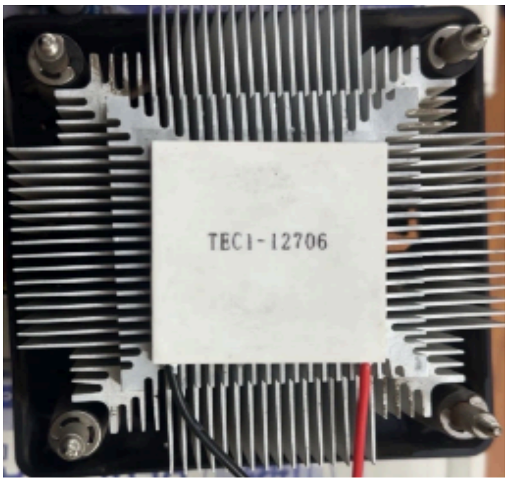
The laser and temperature control system is essential for stable ODMR measurements, as both the laser diode performance and the quantum properties of silicon carbide defects are temperature-dependent. The current implementation employs a custom power supply based on a computer **SMPS** (Switched-Mode Power Supply) and temperature control using a **Peltier module**.

The power supply for the laser diode is built using a repurposed computer **SMPS**, which provides:

- Stable voltage output
- Sufficient current capacity
- Multiple voltage rails for different components
- Short-circuit protection
- Overcurrent protection

Temperature control is achieved through a **Peltier module** (thermoelectric cooler) system with:

- **Peltier element** for active cooling/heating
- Temperature sensor (typically a thermistor)
- Heat sink for thermal management
- Thermal interface materials for efficient heat transfer



The system includes protection features such as:

- Over-temperature shutdown
- Current limiting for the laser diode and Peltier module
- Thermal insulation to prevent condensation

These components are designed with both performance and safety in mind, incorporating features to protect the sensitive laser diode and ensure reliable operation during extended measurement sessions
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2.4. Future Implementation – Lock-in Amplifier

In the next phase of the project, a **Lock-in Amplifier** will be implemented using the **Red Pitaya** platform to enable the detection of small signals in noisy environments. This component will be crucial for detecting the optical signals from **silicon carbide defects** during ODMR measurements.

The **Red Pitaya** is an open-source hardware platform that combines a field-programmable gate array (**FPGA**) with high-speed analog-to-digital (**ADC**) and digital-to-analog (**DAC**) converters. Key specifications that make it suitable for this application include:

- 125 MS/s sampling rate
- 14-bit resolution ADCs and DACs
- Xilinx Zynq SoC (dual-core ARM Cortex-A9 + FPGA)
- Programmable inputs and outputs
- Network connectivity for remote control

The planned lock-in amplifier implementation will perform the following functions:

- Reference signal generation for modulation of the RF output
- Synchronous detection of the optical signal
- Phase-sensitive demodulation
- Low-pass filtering to improve signal-to-noise ratio
- Amplitude and phase measurement
- Data buffering and transfer to the host computer

The digital implementation on the **Red Pitaya** will offer several advantages over traditional analog lock-in amplifiers, including flexibility in filter characteristics, precise control of phase relationships, and digital data recording and analysis.

2.5. Future Implementation – Signal Processing

In future phases of the project, signal processing and analysis algorithms will be developed to transform raw data from the lock-in amplifier into meaningful magnetic field measurements. These algorithms will be essential for extracting relevant information from the ODMR spectra.

The planned ODMR signal processing pipeline will include:

- Data acquisition from the lock-in amplifier
- Pre-processing to remove artifacts and baseline drift
- Averaging to improve signal-to-noise ratio
- Peak detection and characterization
- Spectral fitting to theoretical models
- Magnetic field calculation from spectral features

Algorithms to be implemented for signal processing include:

- Moving average and **Savitzky-Golay filtering** for noise reduction
- Polynomial baseline correction
- **FFT-based** spectral analysis
- Non-linear least squares fitting of Lorentzian or Gaussian line shapes
- **Principal Component Analysis** (**PCA**) for multivariate data

The ODMR spectrum from **silicon carbide defects** contains characteristic resonance features that shift with magnetic field strength. By precisely measuring these resonance frequencies and applying calibration factors, the system will be able to determine magnetic field components with high sensitivity.

3. Scope and Next Steps

The current state of the project includes a functional **RF synthesizer** controlled by an **Arduino** microcontroller, a **Python GUI** for interfacing with the RF synthesizer, and a custom power supply with temperature control system using a computer **SMPS** and **Peltier module**.

The next steps in the project development include:

1. **Integration of optical components**:

    - Setting up the laser diode with proper collimation and focusing optics
    - Implementing optical filters for signal isolation
    - Designing a sample holder for silicon carbide chips

2. **Implementation of the Lock-in Amplifier**:

    - Programming the **Red Pitaya** platform for lock-in detection
    - Calibrating the lock-in amplifier with known reference signals
    - Integrating the lock-in amplifier with the existing system components

3. **Development of signal processing algorithms**:

    - Implementing data acquisition routines
    - Developing spectral analysis algorithms
    - Creating calibration procedures for magnetic field measurements

4. **System testing and optimization**:

    - Characterizing system performance with known magnetic fields
    - Optimizing measurement parameters for maximum sensitivity
    - Identifying and addressing sources of noise and interference

5. **GUI enhancement**:

    - Expanding the GUI to control all system components
    - Adding data visualization capabilities
    - Implementing data export and analysis features

The modular design of the system allows for incremental development and testing of individual components before full integration. This approach reduces development risks and enables early identification of potential issues.

Upon completion, the ODMR system will be capable of detecting magnetic fields using **silicon carbide defects** with high sensitivity and spatial resolution. The system will be significantly more affordable than commercial alternatives while maintaining acceptable performance for many applications in research and education.

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