EN2160 - Electronic Design Realization

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EN2160 Electronic Design Realization**)**

RFID Based Warehouse Management System – UHF RFID Reader

Contents

1 Introduction 5
2 Component Selection 5
3 Functional Block Diagram 7
4 System Overview 7
5 Schematic Design 8
  5.1 System Overview 8
  5.2 UHF RFID Reader IC 8
  5.3 External Power Amplifier 9
  5.4 Carrier Cancellation 9
  5.5 Antenna Switch 10
  5.6 RF Shield 10
  5.7 USB Supply/UART Bridge 11
  5.8 Microcontroller IC 11
  5.9 Supply LDOs 12
  5.10 External Interfaces 12
6 Hardware Description 13
  6.1 RF Circuit 13
  6.2 Microcontroller and connections 15
  6.3 Boot Mode 16
  6.4 Power Supply 17
  6.4 Test Points 17
  6.5 Probing RF Signals 18
7 PCB Design 19
  7.1 Introduction 19
  7.2 Layer Stack Up Selection 19
  7.3 Key Concepts 20
  7.4 Layout Details 21
  7.5 PCB Specifications 24
  7.6 Additional Details 24
  7.7 Conclusion 24
8 Bill of Materials 25
9 Enclosure Design 29
  9.1 SolidWorks Design 29
  10.2 Printed Enclosure 30
10 Antenna Design 31
  10.1 Introduction 31
  10.2 Basic equations and theory used 31
  10.2.1 Microstrip Patch Antennas 31
  10.2.2 PIFA – Planar Inverterd F Antennas 35
  10.4 Key Design Considerations 39
  10.5 Simulation and Optimization 39
  10.6 Antennas Designed 39
  10.6.1 Simple Patch Antenna 40
  10.6.2 Microstrip Antenna with Inset Feed 41

10.5.3 PIFA- Planar Inverted F Antenna 43
10.6.4 IFA- Inverted F Antenna 44
10.7 Fabrication and Testing 46
10.8 Anenna Specifications 46
10.9 Integration with RFID Reader 46
10.10 Key Concepts 46
10.11 Final PCB Design of IFA – Inverted F Antenna 46
10.12 Conclusion 48
11 System Integration 48
11.1 Firmware Programming 48
12 Soldering (Antenna and PCB) 49
13 Testing (Antenna and PCB) 50
14 Assembly 50
15 Future Developments & Acknowledgements 50
15.1 Future Developments 50
15.2 Acknowledgement 50
16 Datasheets 51
17 Datasheets 51
Appendix 52
Review Declaration 55

Abstract

This project involves the design and development of an Ultra-High Frequency (UHF) RFID reader intended for warehouse management systems. The RFID reader aims to streamline inventory tracking by providing reliable, real-time updates and reducing manual errors. The project includes the creation of detailed circuit schematics, a 6-layer PCB layout, and the selection of key components such as the ST25RU3993 IC and STM32 microcontroller.

A critical aspect of the design is the Planar Inverted-F Antenna (PIFA), which has been meticulously designed and optimized using advanced simulation tools to ensure optimal performance in reading RFID tags over a range of at least 2 meters. Through the application of these simulation tools and rapid prototyping, the design achieves high gain and efficiency while maintaining compactness. Despite facing challenges such as component delays and complex impedance control, the team has successfully progressed to the prototyping and testing phase. This project demonstrates a comprehensive approach to designing a cost-effective, high-performance RFID reader tailored to the needs of modern warehouse environments.

To address the multifaceted nature of the project, a cross-functional team structure has been adopted. Each team, consisting of two members, is assigned to a specific module—UHF Portal, HF Handheld Scanner AND HF forklift scanner Module. This strategic team alignment focuses on achieving learning outcomes of the EDR module. Each team have to design their own PCB and enclosure to ensure the proper understanding of the concepts.

This report delves into the key components of the UHF RFID Reader including RFID tags/stickers, readers, antennas, and software integration. Furthermore, it outlines the benefits of implementing such a system including improved inventory accuracy, enhanced operational efficiency, reduced labor costs, and increased customer satisfaction. Practical considerations such as system design, implementation challenges, and cost analysis are also discussed. Overall, this report serves as a valuable resource for organizations seeking to optimize their warehouse operations through the adoption of RFID technology.

1 Introduction

In an era characterized by the increasing integration of digital technologies into everyday life, the demand for efficient and versatile RFID (Radio-Frequency Identification) solutions continues to grow. Our project addresses this demand with the development of an advanced UHF RFID reader equipped with innovative features to facilitate the evolving needs of warehouse management.

- This product is equipped with features tailored to the demands of warehouse environments, including:
- Seamless Inventory Tracking: Leveraging RFID technology, our reader offers fast and reliable identification and tracking of inventory, minimizing manual intervention and reducing the risk of errors.
- Real-time Data Integration: Integration with Wi-Fi technology enables seamless data transmission to centralized warehouse management systems, providing real-time visibility into inventory status and movements.
- User-Friendly Interface: A high-resolution LED screen and intuitive user interface enhance usability and productivity, allowing warehouse staff to efficiently navigate through inventory data and perform scanning tasks with ease.

This report aims to provide stakeholders, developers, and end-users with a comprehensive understanding of the RFID reader's capabilities and functionalities, demonstrating how it addresses the challenges of modern warehouse management with cutting-edge technology.

2 Component Selection

To fulfil our requirements, after a decent amount of time in researching different datasheets, we selected the components that adhere to our circuit's performance. Since we used the High-power RFID reader system based on ST25RU3993 User Manual for the PCB Design we used components that were recommended by them.

Below are some major components in our PCBs.

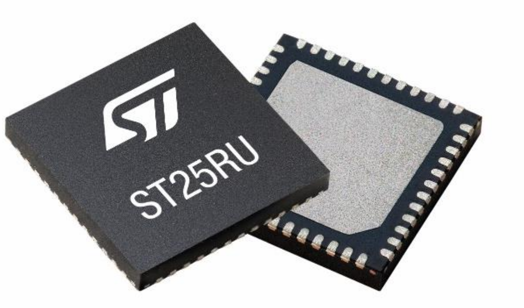


Fig: ST25RU3993 IC

- **The ST25RU3993 IC** is developed by STMicroelectronics, is a high-performance UHF RFID reader IC designed for demanding warehouse management systems. Here are the key features that make it suitable for our project:

  - **High Sensitivity and Fast Read Rate:** Ensures reliable detection and reading of RFID tags over a range of at least 2 meters, crucial for efficient and real-time inventory tracking.

- **Wide Frequency Range and Multi-Protocol Support:** Operates across a wide frequency range and supports multiple RFID protocols, ensuring compatibility with various RFID tags and systems used globally.

- **Integrated Antenna Tuning and Matching:** Simplifies the design process and enhances overall performance by including features for antenna tuning and matching.

- **Low Power Consumption:** Suitable for battery-powered applications, ensuring long-term operational efficiency without frequent recharging or battery replacements.

- **Robust Communication Protocols and Data Integrity**: Supports robust communication protocols that ensure data integrity and security during transmission, critical for maintaining accurate and secure inventory records.

- **Comprehensive Development Tools and Support:** Facilitates rapid prototyping and development with a comprehensive suite of tools and support from STMicroelectronics.

- **Proven Reliability:** Extensively tested in various RFID applications, proving its reliability and robustness in real-world conditions.

In summary, the ST25RU3993 IC's high sensitivity, wide frequency range, integrated antenna tuning, low power consumption, robust communication protocols, and proven reliability make it an ideal choice for our UHF RFID reader project.

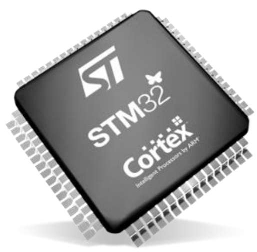


Fig: STM32 Microcontroller

STM32 Microcontroller - In our UHF RFID reader design, the STM32 microcontroller plays a pivotal role in orchestrating the overall system operation. Renowned for its robust performance and flexibility, the STM32 provides the computational power necessary for processing RFID tag data, managing communication protocols, and interfacing with the warehouse management system. Its extensive I/O capabilities and efficient power consumption make it an ideal choice for ensuring reliable, real-time inventory tracking in dynamic warehouse environments.

3 Functional Block Diagram

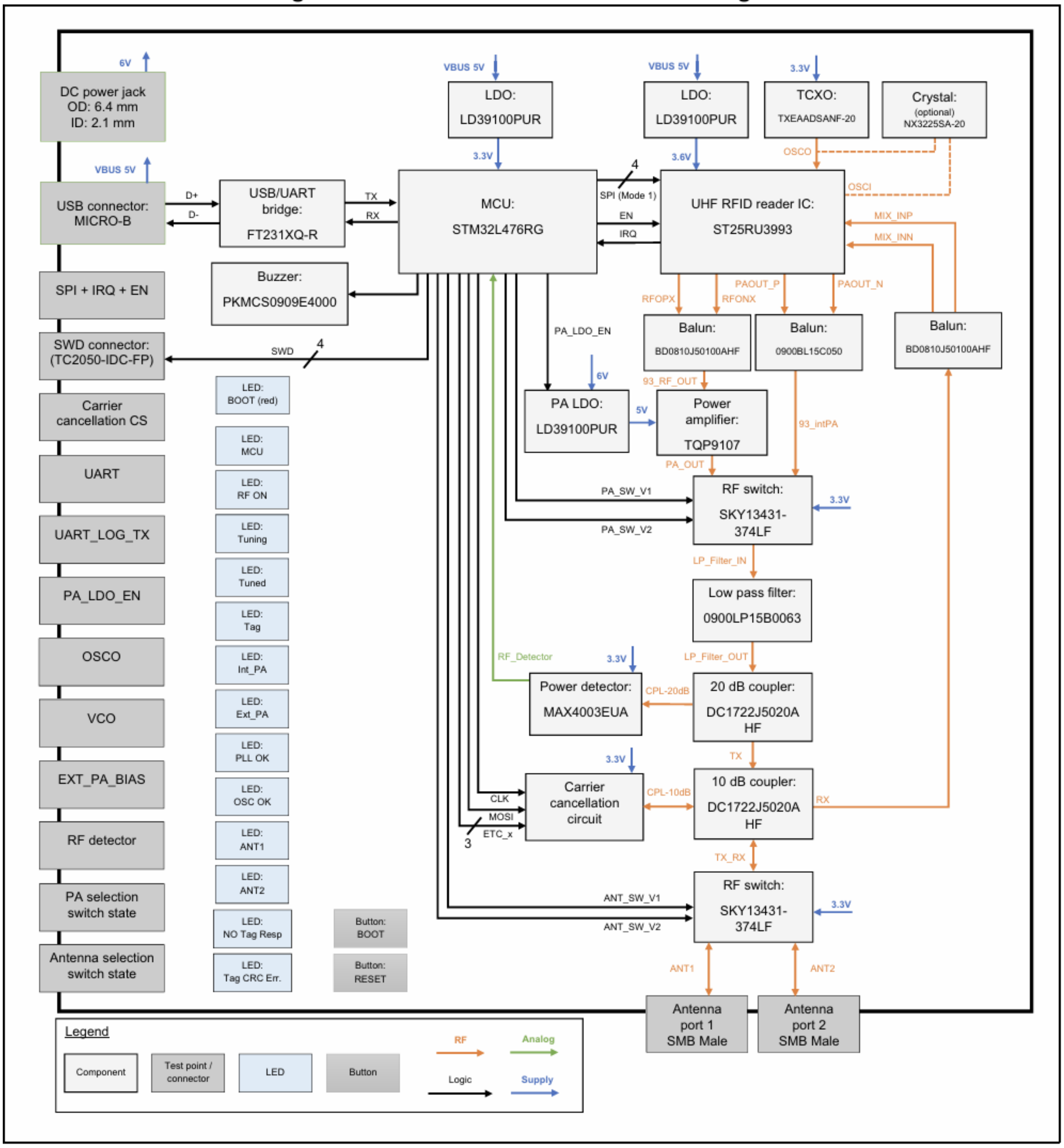


Fig: Functional Block Diagram

4 System Overview

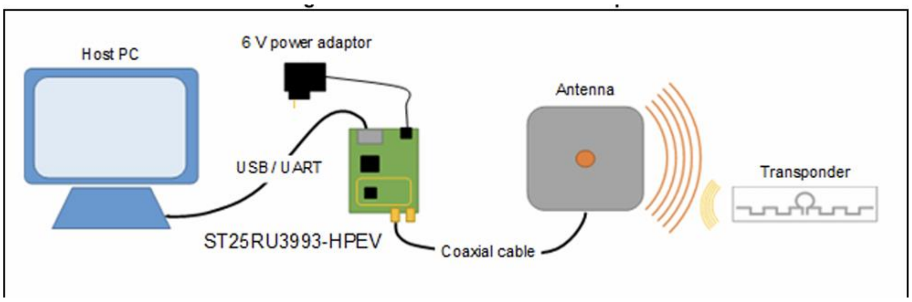


Fig: System Overview

5 Schematic Design

Please refer to the Design Methedology document for clearer Schematics.

5.1 System Overview

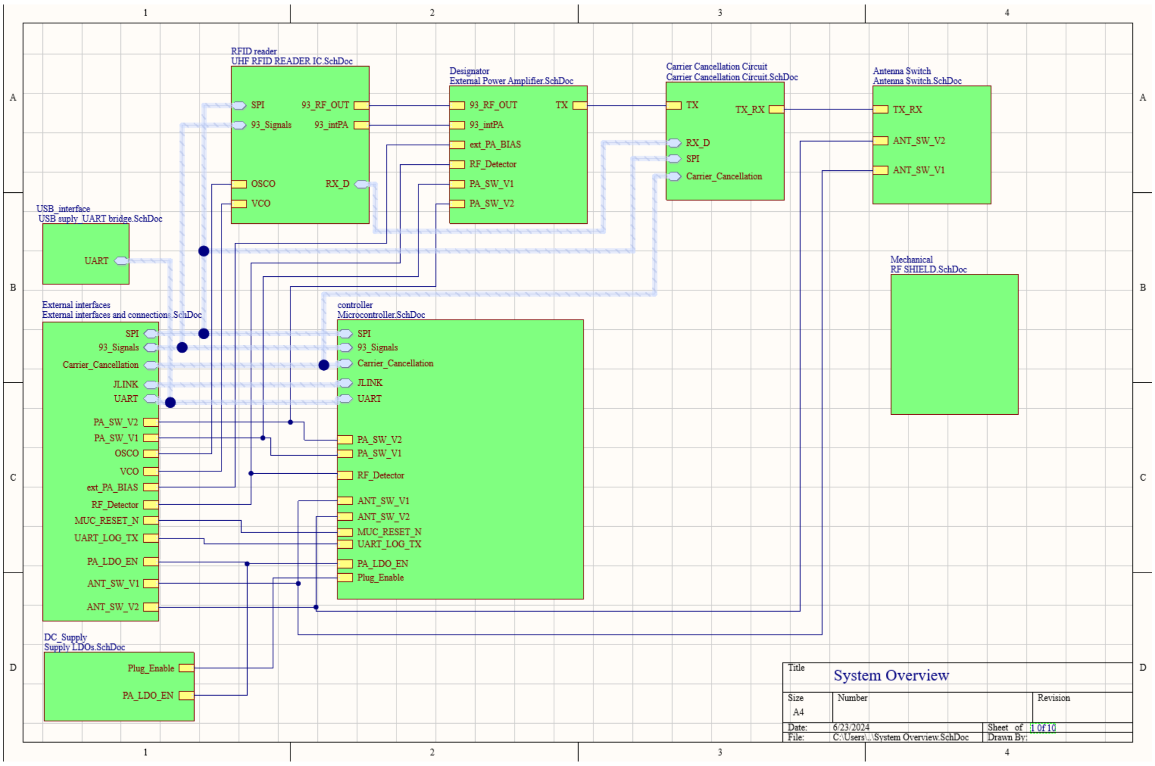


Fig: System Overview

5.2 UHF RFID Reader IC

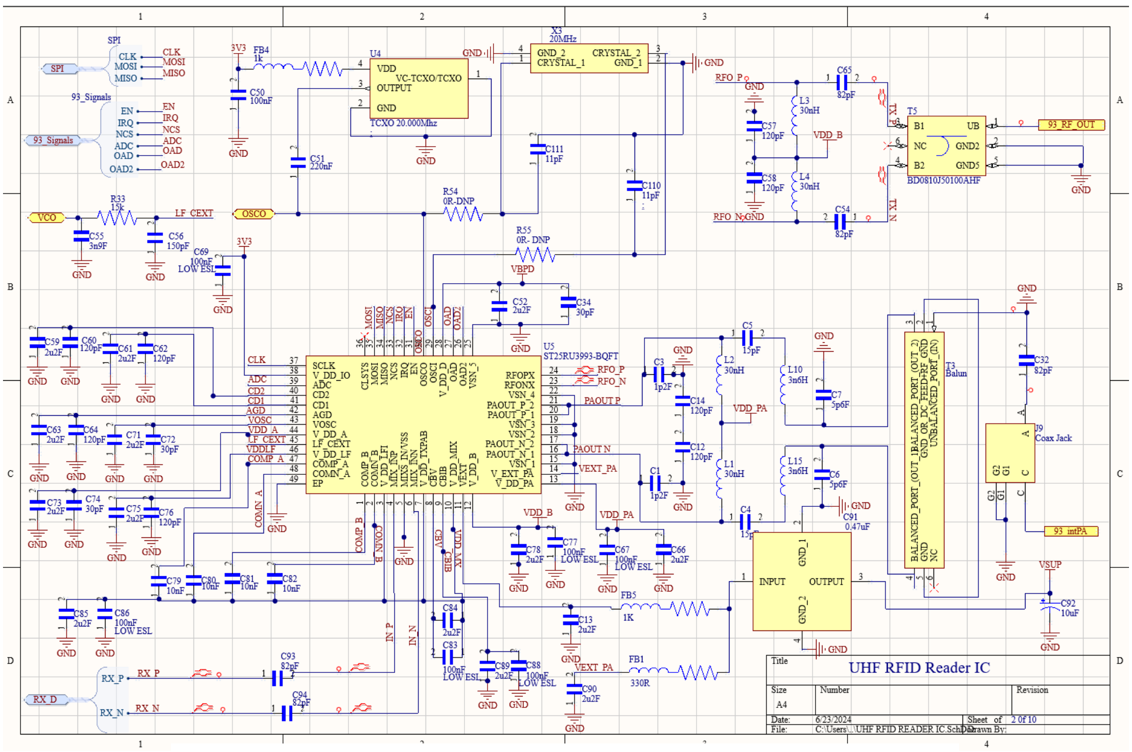


Fig: Schematic of UHF RFID Reader IC Circuit

5.3 External Power Amplifier

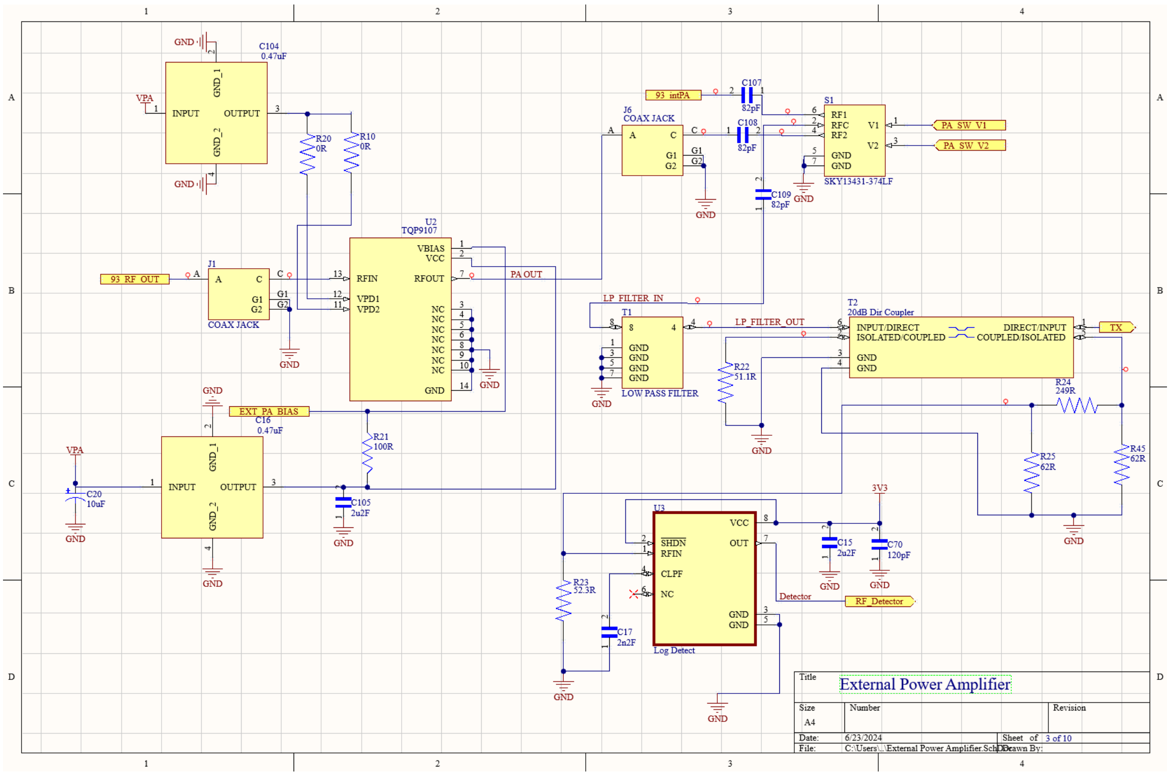


Fig: Schematic of External Power Amplifier

5.4 Carrier Cancellation

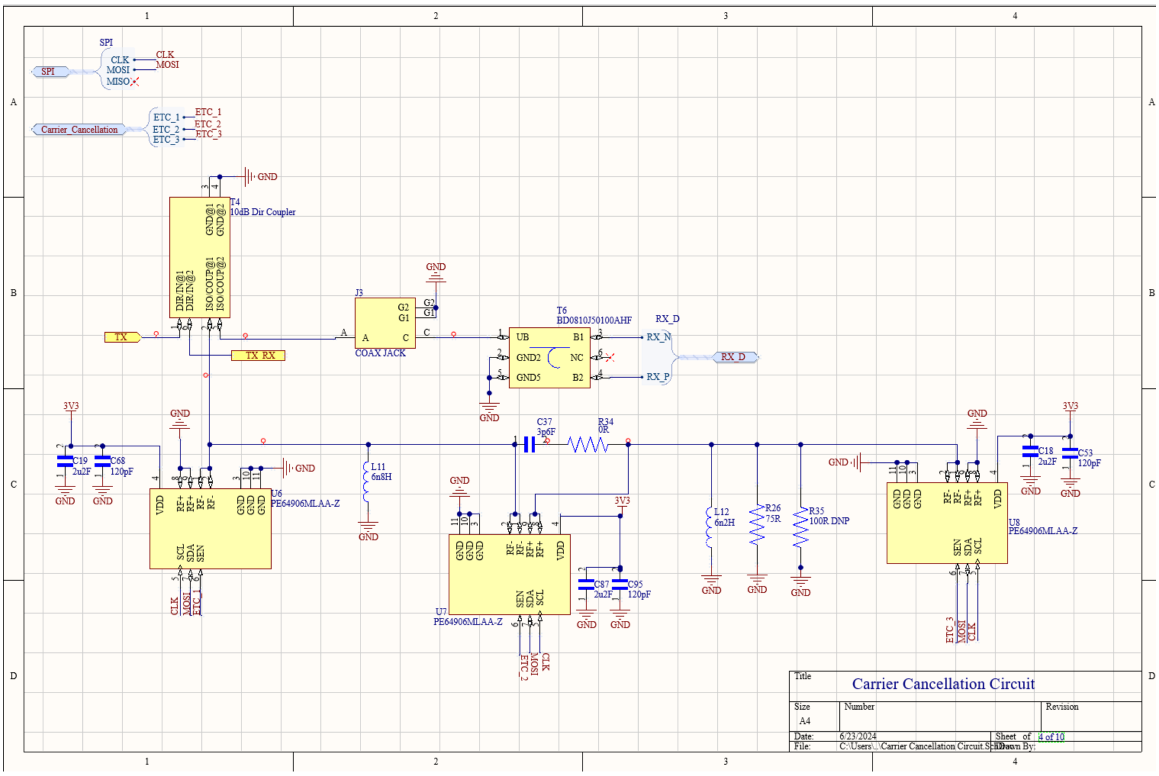


Fig: Schematic of Carrier Cancellation Circuit

5.5 Antenna Switch

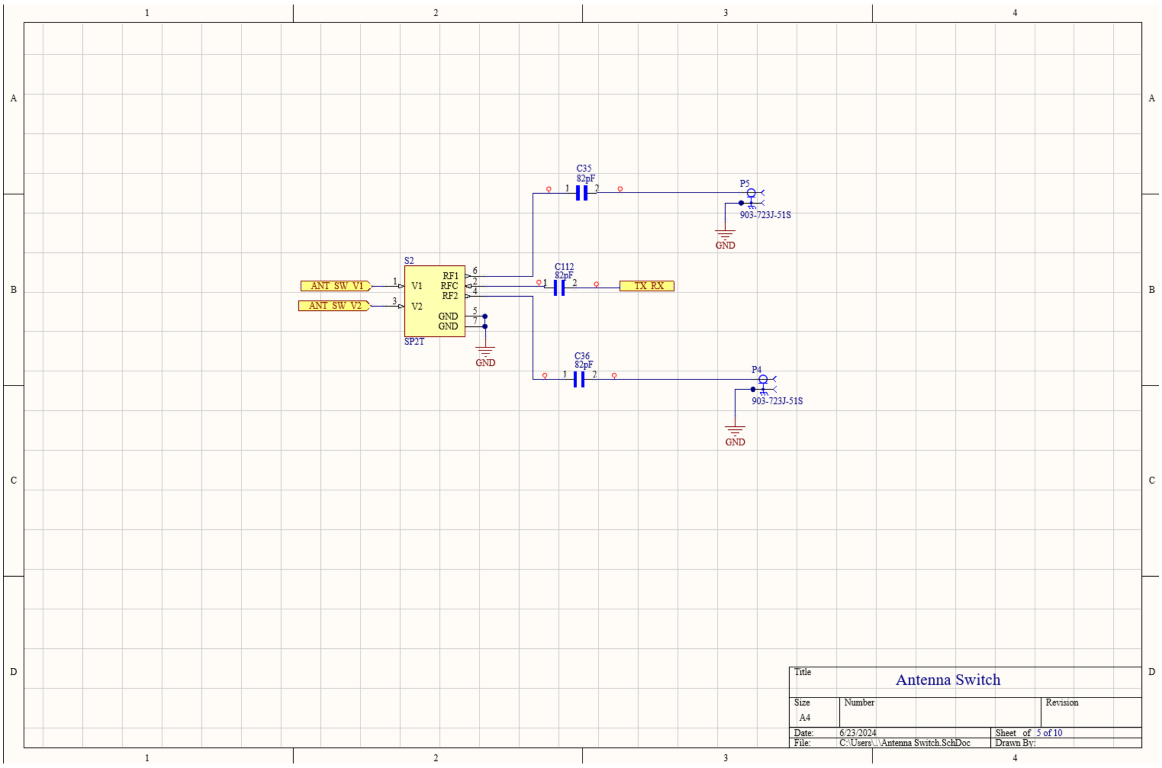


Fig: Schematic of Antenna Switch

5.6 RF Shield

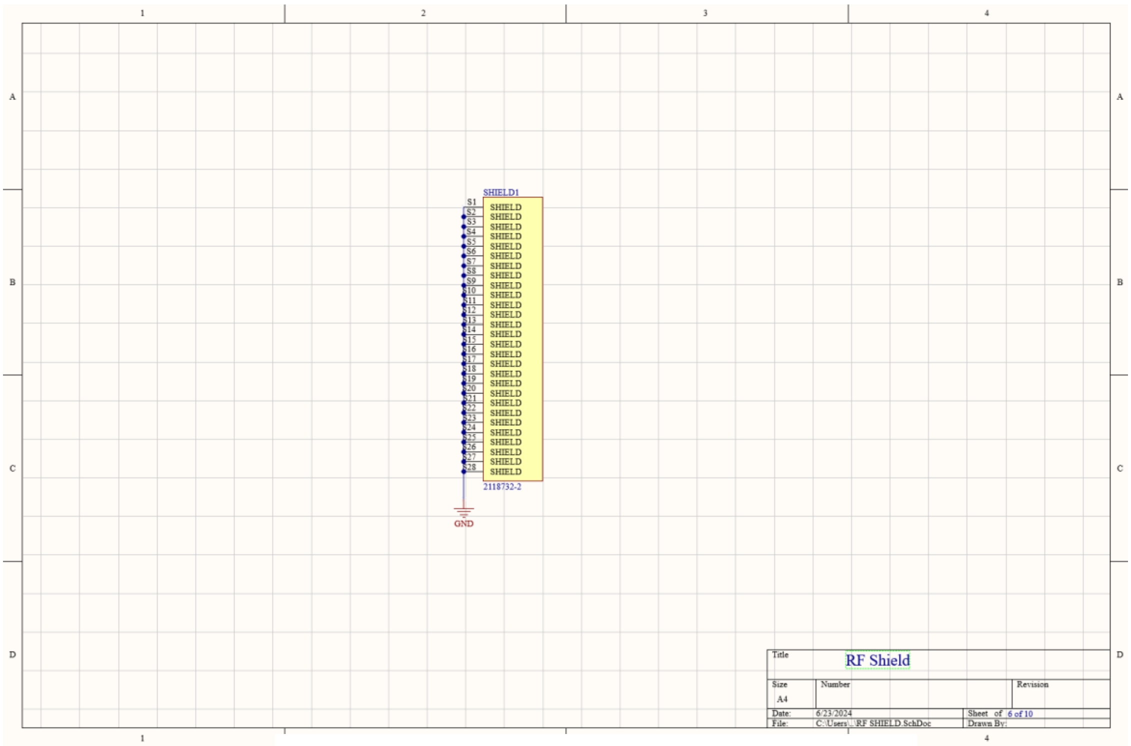


Fig: Schematic of RF Sheild

5.7 USB Supply/UART Bridge

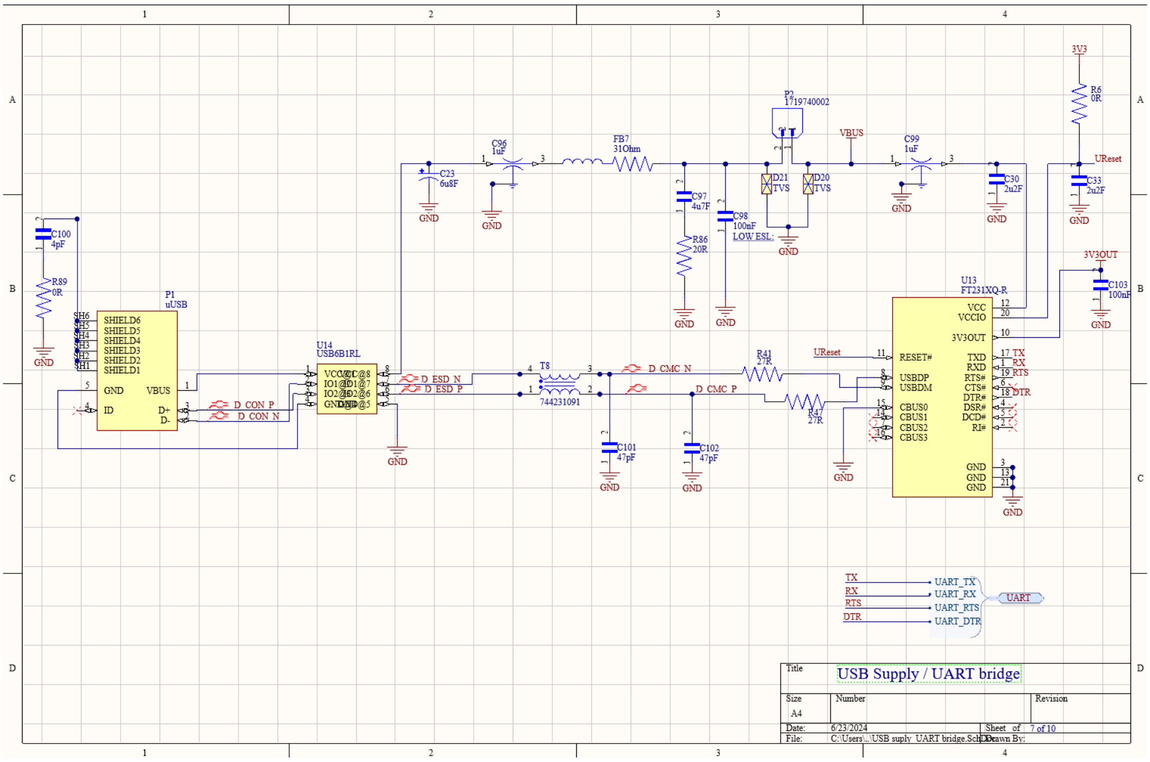


Fig: Schematic of USB Supply

5.8 Microcontroller IC

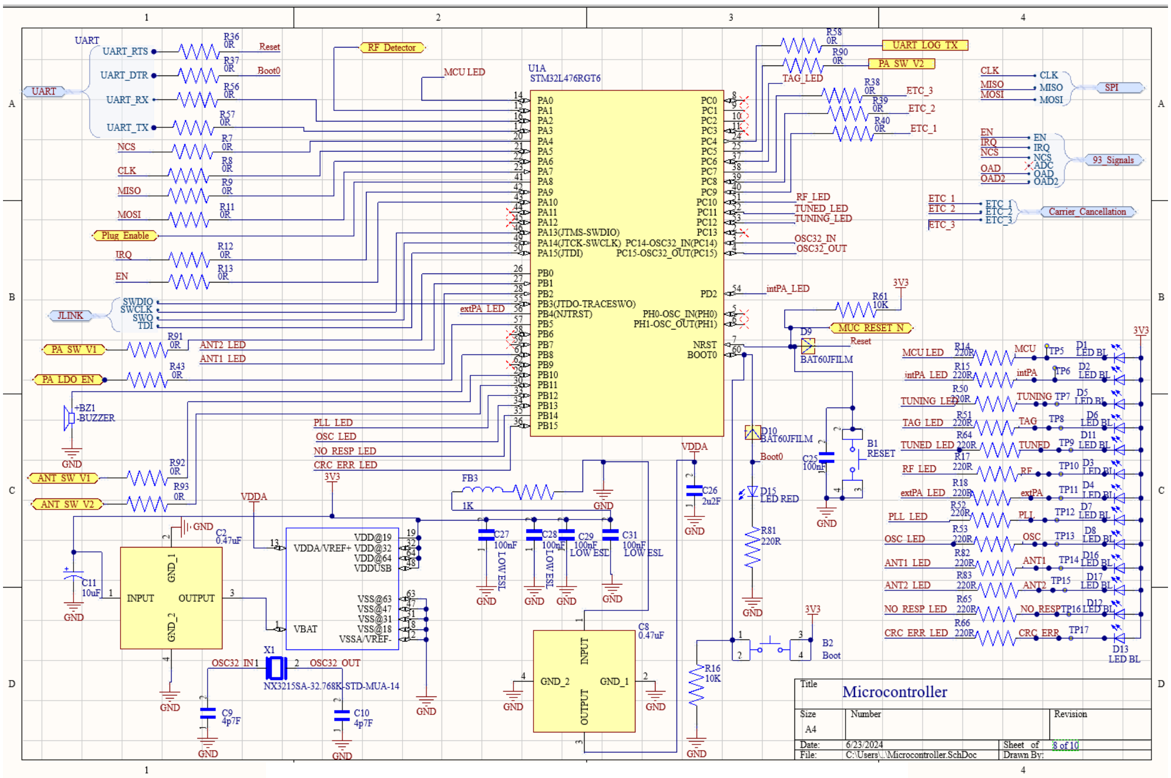


Fig: Schematic of Microcontroller

5.9 Supply LDOs

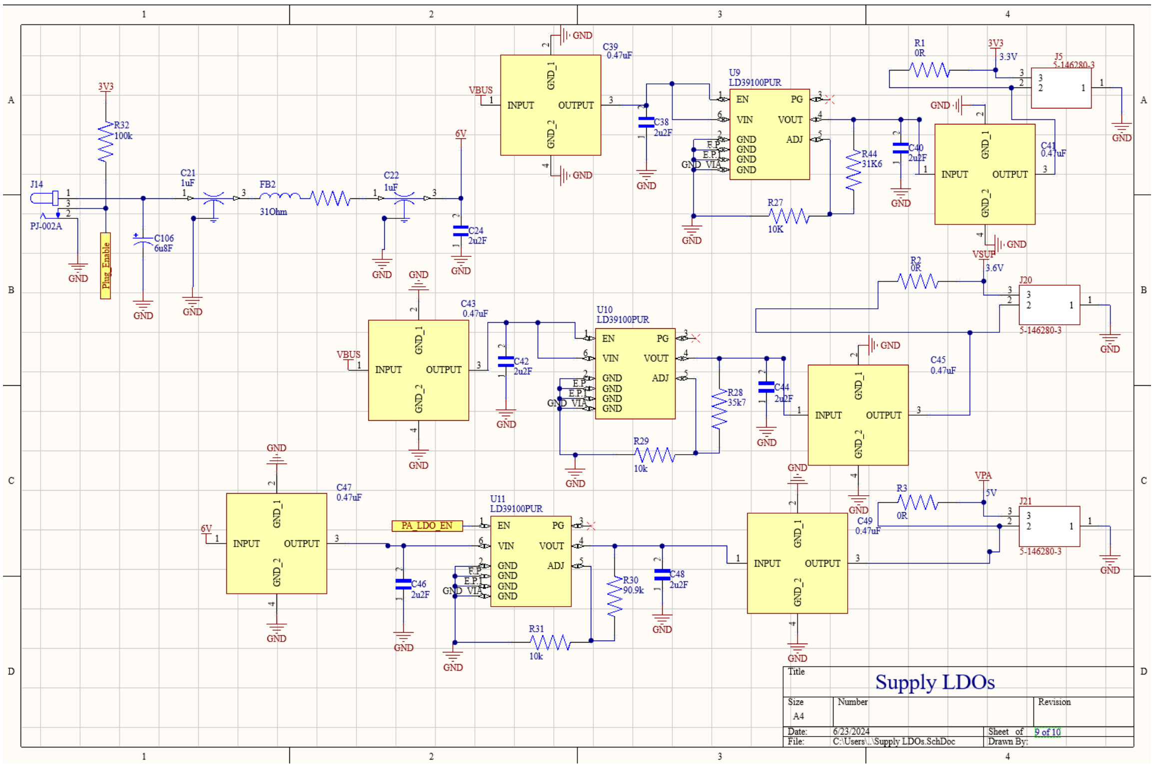


Fig: Schematic of Supply LDOs

5.10 External Interfaces

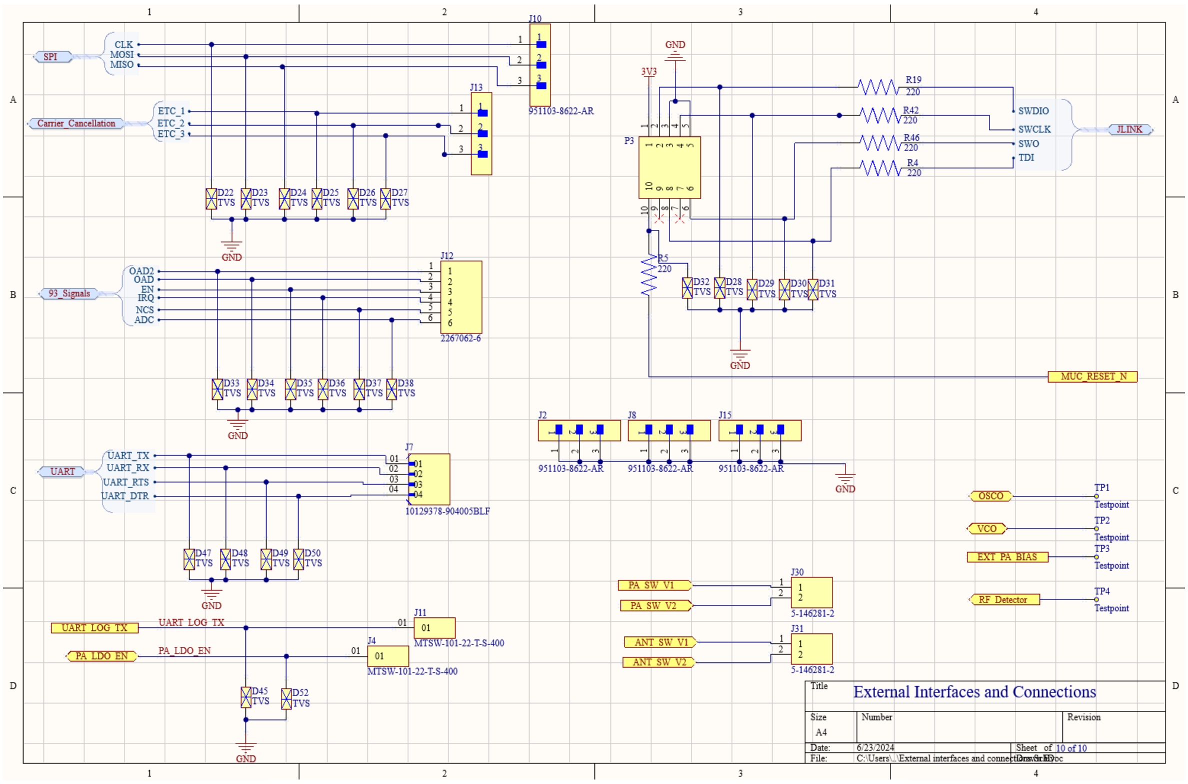


Fig: Schematic of External Interfaces

6 Hardware Description

6.1 RF Circuit

The main component of the RF circuit is the ST25RU3993 device, which receives digital baseband transmit data and commands from the MCU via the SPI interface. It then frames these data and automatically encodes them into PIE symbols. Based on the PIE encoded symbols ST25RU3993 creates a sinusoidal shaped modulation signal (either ASK or PR-ASK), which modulates the RF carrier. ST25RU3993 synthesizes its RF carrier frequency with a VCO / integer-n phase locked loop (PLL). The frequency reference for the PLL can be either a 20 MHz crystal oscillator or a temperature compensated crystal oscillator (TCXO).

The output of the internal PLL- charge pump is connected to LF_CEXT (pin 45), and the external part of the loop filter is placed in close proximity to it. An additional low-pass filter stage is integrated in ST25RU3993 and is part of the loop filter circuit. The loop filter output is the control voltage of the internal VCO.

The ST25RU3993 has two differential output port pairs. The low power output and the internal power amplifier output. Depending on which differential output port pair is activated the modulated carrier frequency will be amplified and output accordingly. The low power output is intended for external signal amplification for a long read range configuration of the ST25RU3993-HPEV reader.

The low power output with its differential output pin pairs RFONX (23) and RFOPX (24) is connected to a 2:1 balun, where the transmit signal is transformed from a 100 differential to 50 Ω single-ended signal. The output stage of the low power output is supplied by the VDD_B voltage generated and regulated by ST25RU3993 itself. L3 and L4 act as a RF choke, C57 and C58 as bypass capacitors and C65 and C54 as DC blocking capacitors. The signal then proceeds to the external power amplifier to generate a high-power output signal with approximately 31 dBm in ST25RU3993-HPEV default transmit power configuration.

The internal power amplifier is used for the short read range configuration of the reader. The output pins of the internal power amplifier are PAOUT_N (16, 17) and PAOUT_P (20, 21). A matching network and a 1:1 balun transforms the output of the internal power amplifier to a 50 Ω single-ended signal. The internal power amplifier is supplied by the on-chip generated and regulated voltage VDD_PA. L1, L2 are acting as RF chokes, C12 and C14 are bypass capacitors. After the balun the output power of the internal power amplifier is tipically 20 dBm.

Both RF output options the external power amplifier and the output of the internal power amplifier are connected to an RF-switch which is controlled by the PC software (GUI) of the ST25RU3993-HPEV reader. Only one RF output option can be active at a time. Note a UHF RFID reader reference would typically offer only one RF output and hence the PA RF-switch would be stripped from the design avoiding it's introduced insertion loss of ~0.5 dB. So would be the DC blocking capacitors which this RF-switch requires on all its RF terminals. The output of the RF-switch is connected to a low-pass filter which attenuates the second and third harmonic of the carrier frequency. The filtered transmit signal is then connected to a 20 dB directional coupler, which takes a negligible small portion of the transmit power, which is further attenuated by a pi-pad attenuator. The limited TX power sample is then fed to the input a logarithmic power detector that converts the RF power to a corresponding DC voltage. The output DC voltage of the power detector versus the generated RF power is shown in the figure below.

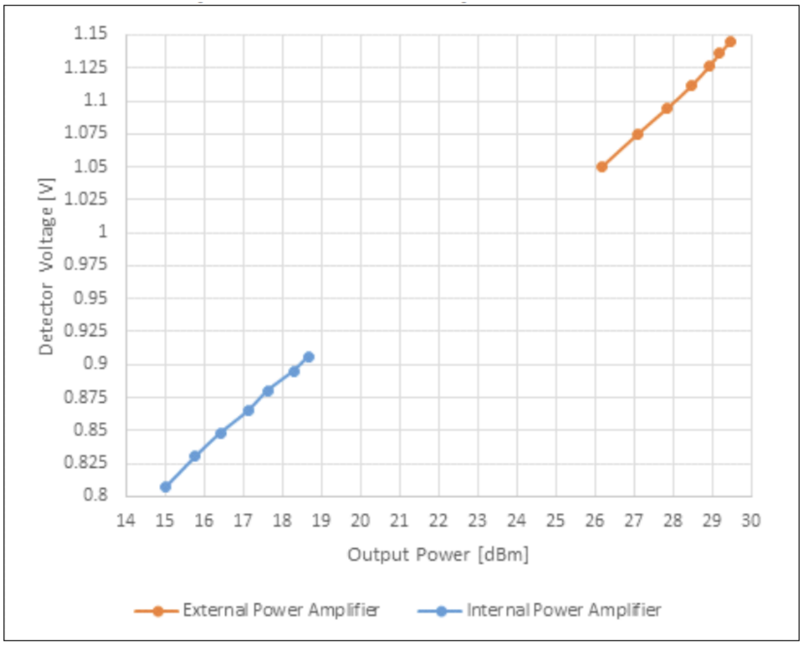


Fig: Power Detector Voltage Characteristics

The DC output voltage of the power detector is connected to an ADC input pin (PA1) of the microcontroller.

The majority of RF transmit power which passes through the 20 dB directional coupler is fed to the main directional coupler. The main directional coupler has a coupling factor of 10 dB and acts as the directional unit which should isolate the transmit from the receive path of ST25RU3993. The main directional coupler plays a very important role in the RFID reader system as its parasitics have a great influence on the sensitivity of the reader. The main directional coupler essentially has four terminals:

1. Input
2. Direct
3. Coupled
4. Isolated

The direct terminal is connected to the second RF switch in the reader system. This switch directs the transmit power to either antenna port 1 or antenna port 2. The antenna switch again requires DC blocking capacitors on all its RF terminals. Both antenna ports are SMB (male) type.

To avoid reducing the sensitivity of the reader the self-jamming signal reaching the receiving inputs of ST25RU3993 must be minimized. The self-jamming signal comprises reflections from the antenna (S11) and the leakage across the main directional coupler. To minimize it a carrier cancellation circuit is connected to the coupled port of the main directional coupler.

The carrier cancellation circuit is able to change its impedance and hence to reflect a certain amount of the coupled power back into the directional coupler. This reflected signal is combined with the self-jamming signal at the isolated port of the main directional coupler. The isolated port of the main directional coupler is connected to the receiving pins of ST25RU3993. If the signal reflected by the carrier cancellation circuit has the same amplitude and opposite phase of the self-jammer the signals cancel them out and vanish. The main components of the CCC are three digital tunable capacitors controlled by the STM32L476RG microcontroller via SPI. The lumped components of the carrier cancellation circuit help to define its tuning range around 50 Ω and define the impedance step created by one LSB change of a digital tunable capacitor. The isolated port of the main directional coupler is connected to a 2:1 balun to transform the incoming tag response signal to a 100 Ω differential signal that is fed into ST25RU3993 receiver section at pins MIX_INP (4) and MIX_INN (6).

6.2 Microcontroller and connections

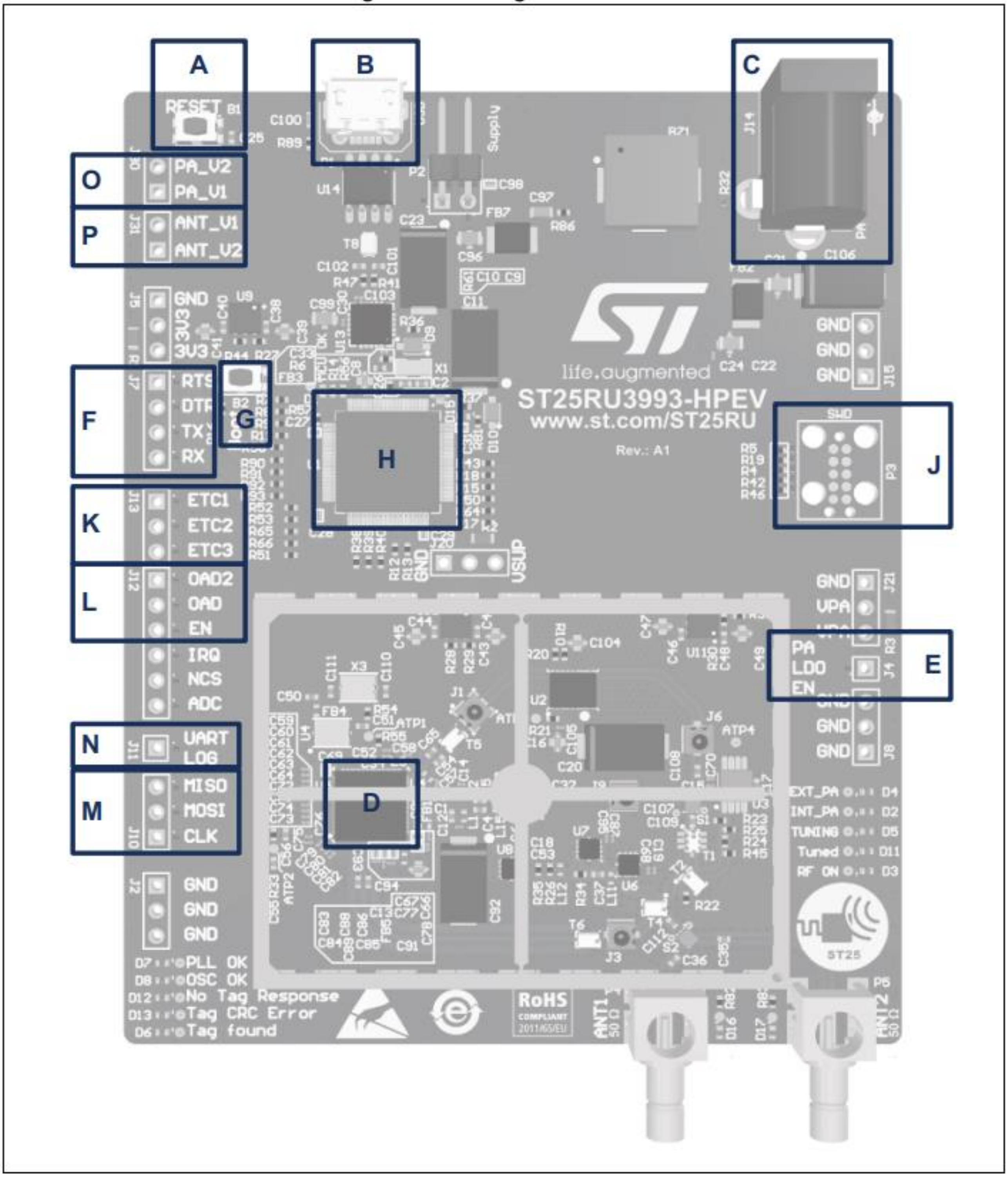


Fig: Main Digital Interfaces

A	MCU reset button
B	USB receptacle: Micro, B-Type
C	6V DC power connector: 5 mm barrel connector
D	ST25RU3993 Rain (UHF) RFID reader IC
E	Enable line connection of power amplifier LDO
F	UART interface connections
G	MCU boot mode button
H	STM32L476RGT6 (Arm® 32-bit Cortex®-M4)
J	SWD debug interface connections
L, M	SPI bus interface connections
N	UART_LOG connection for debugging purposes
K	Carrier cancellation circuit (CCC) SPI chip select lines
O	PA output selection switch state
P	Antenna port selection switch state

Table: MCU Interfaces and Buttons

The MCU is supplied by 3.3 Volts, regulated by an adjustable LDO. The clock source is an external crystal generating 32.768 kHz, connected to OSC32_in (3) and OSC32_out (4). It interfaces the host PC via UART for which a USB/UART bridge is used.

The MCU communicates with the ST25RU3993 via an SPI interface controlling the ST25RU3993 lines ENABLE and IRQ. The SPI interface operates in mode 1 with a 6 MHz serial clock. The SPI interface is also used to control the digital tunable capacitors for the carrier cancellation circuit.

The MCU controls the RF switches for changing the power amplifier and the active antenna port. The analog output of the RF power detector is connected to one of its ADC inputs (PA1) to convert the DC voltage corresponding to the transmit RF power into a digital representation. The LDO for the external power amplifier is enabled by the MCU, making it possible to completely shut down the external power amplifier when RF power needs to be OFF, e.g. as required for carrier sense (LBT). One pin (UART LOG) is reserved to act as a generic debug pin or to be programmed as a trigger output for an external measurement equipment.

6.3 Boot Mode

To enter the STM32L476RG boot mode press and hold the BOOT button (1) while the RESET button (2) is pressed. At this point the boot mode is active and both buttons can be released.

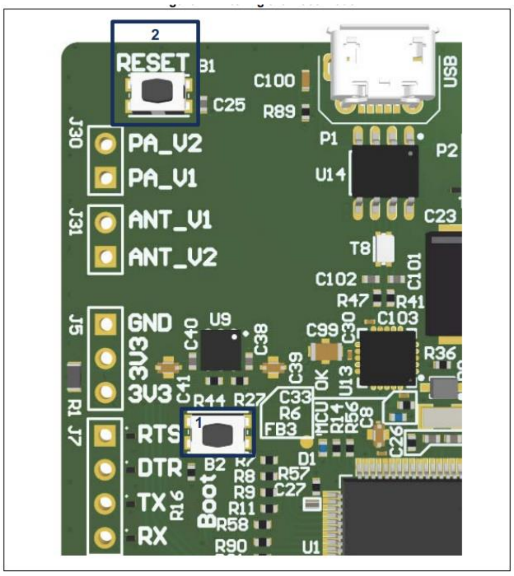


Fig: Boot Mode

6.4 Power Supply

The ST25RU3993-HPEV is supplied through the USB Interface (VBAT) and an external 6 V supply connected to J14 a DC power jack. J14 has a hot inner contact with 2.1 mm diameter suitable for a 5.5 mm barrel plug.

The 5V (VBAT) supply rail is distributed to two low-dropout regulators which supply:

- LDO U9 – for powering digital components (3V3)
- LDO U10 - for powering RF components (VSUP)

The 6 V DC input is dedicated to supply the power amplifier supply via an LDO U11 regulating the supply rail VPA.

Voltage Domain	Voltage
3V3	3.3
VSUP	3.6
VPA	5.0

Table: Typical Voltage Levels

6.4 Test Points

There are several test points on the PCB to test and evaluate the PCB.

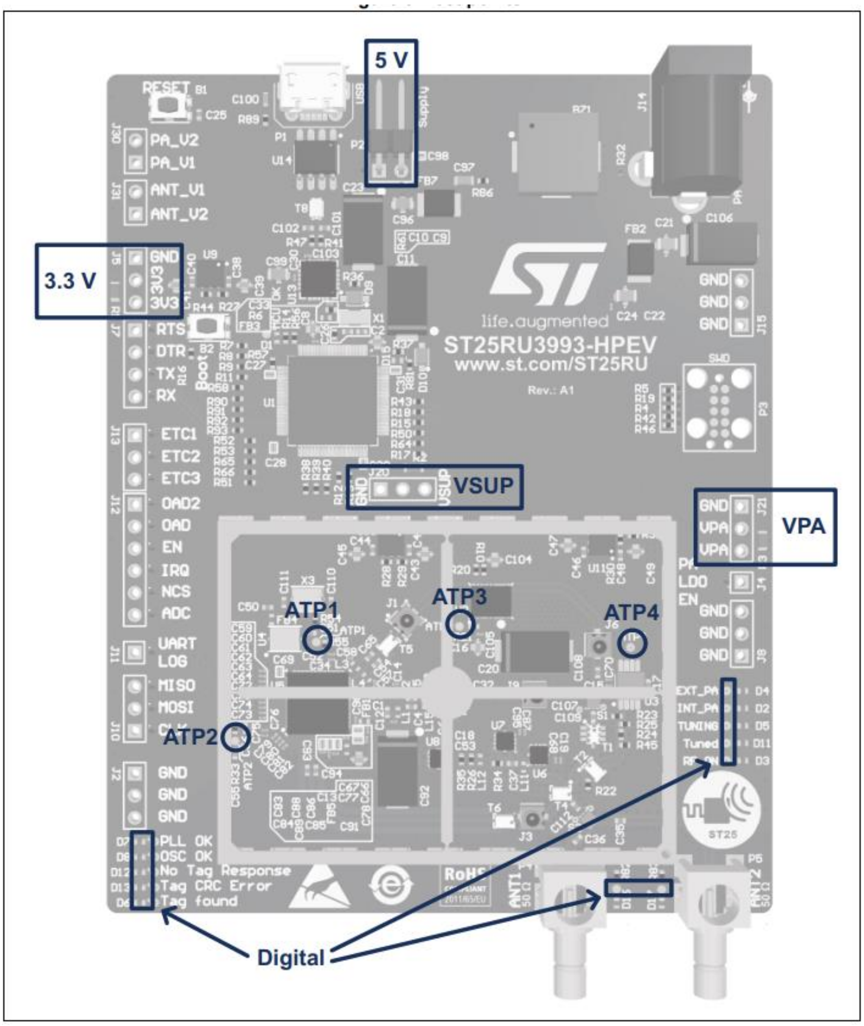


Fig: Test points

6.5 Probing RF Signals

The ST25RU3993-HPEV board features four RF test points to measure RF power levels in-circuit. The test point connectors have a switch built-in that disconnects the remainder of the circuit when the test adapter (MS-156-HRMJ-2) is mated. This allows the user to perform measurements with a proper line termination.

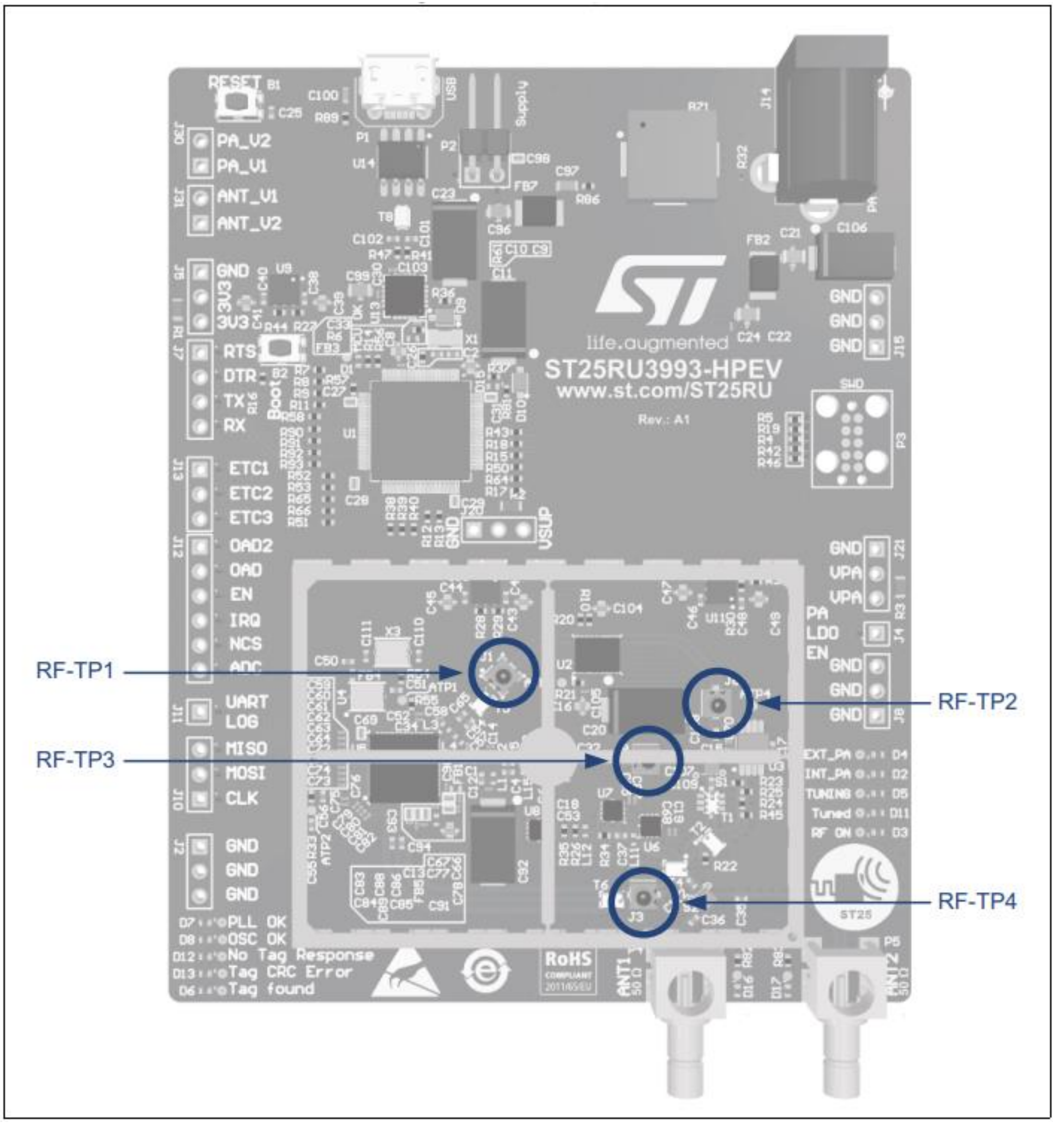


Fig: RF Test points

RF test point	Description	Power Level
RF-TP1	ST25RU3993 RF output signal (single-ended). To evaluate the power and the spectral properties of the RF signal at the low power output.	-1.9 dBm
RF-TP2.	External power amplifier output. To evaluate the power and the spectral properties of the RF signal	33 dB
RF-TP3	Internal power amplifier RF output. To evaluate the power and the spectral properties of the RF signal.	20.5 dBm
RF- TP4	RX signal. To evaluate the self-jammer signal level or a RN16 tag response. When connected no tag communication is possible	-

7 PCB Design

7.1 Introduction

The design and development of a PCB for our project required several strategic decisions and practical adjustments to meet both functional and budgetary constraints. This report details the design process, specific choices made, and the valuable lessons learned throughout this project.

7.2 Layer Stack Up Selection

One of the initial challenges was selecting an appropriate layer stack up for the PCB. The recommended custom layer stack up provided in the guide was deemed too costly. To avoid high expenses, we opted for the closest available stack up from JLCPCB. This decision was based on balancing performance requirements with cost-effectiveness, ensuring that the design remained within budget without compromising on essential functionality.

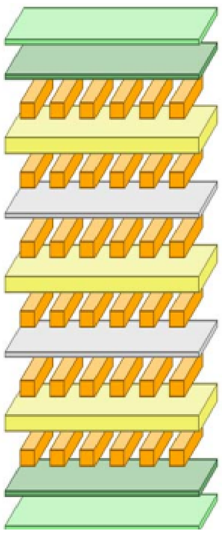
Scheme	Layer				Dielectric	
	Name	**Type**	**Material**	**Th (mm)**	**Material**	**ε_r**
	Top overlay	Overlay				
	Top solder	Solder mask/Coverlay	Surface	0.01016	Solder resist	4.5
	Top layer	Signal	Copper	0.043	-	
	Dielectric 1	Dielectric	Core	0.25	FR-4 (R-1755M)	4.7
	RF GND	Signal	Copper	0.032	-	
	Dielectric 2	Dielectric	Prepreg	0.1	FR-4 (R-1755M)	4.6
	Power	Signal	Copper	0.032	-	
	Dielectric 3	Dielectric	Core	0.1	FR-4 (R-1755M)	4.7
	GND	Signal	Copper	0.036	-	
	Dielectric 4	Dielectric	Prepreg	0.1	FR-4 (R-1755M)	4.6
	Routing	Signal	Copper	0.036	-	
	Dielectric 5	Dielectric	Core	0.25	FR-4 (R-1755M)	4.7
	Bottom GND	Signal	Copper	0.043	-	
	Bottom solder	Solder mask/Coverlay	Surface	0.01016	Solder resist	4.5
	Bottom overlay	Overlay				

Fig: Recommended Layer Stack Up

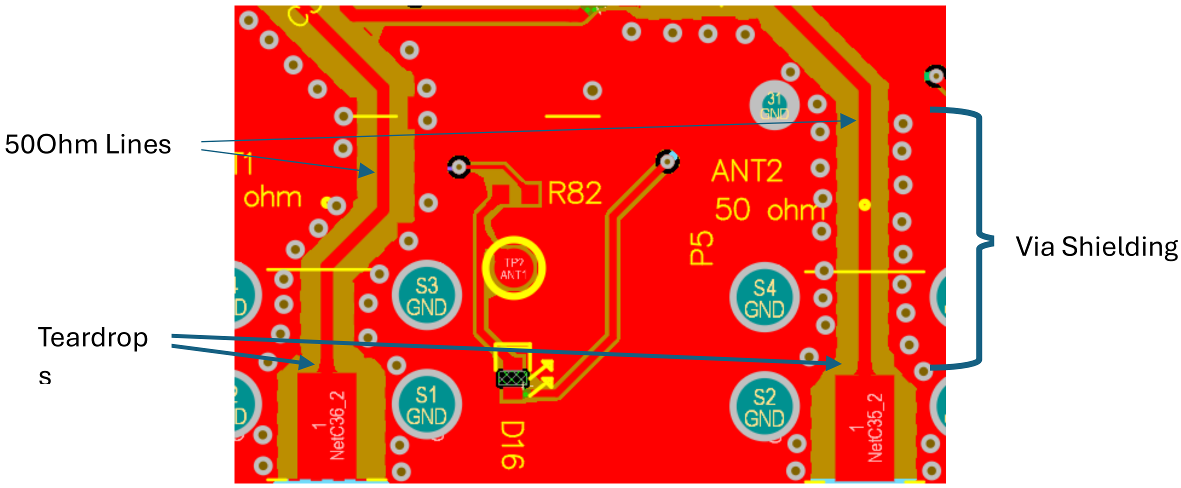
#	Name	Material	Type	Weight	Thickness	Dk	Df
	Top Overlay		Overlay				
	Top Solder	Solder Resist	Solder Mask		0.01016mm	4.4	
1	Top Layer	CF-004	Signal	1oz	0.035mm		
	Dielectric 4	PP-006	Prepreg		0.2104mm	4.4	0.02
2	RF_Ground	CF-003	Signal	1/2oz	0.01801mm		
	Dielectric 2	PP-006	Prepreg		0.4mm	4.4	0.02
3	Power	CF-003	Signal	1/2oz	0.01801mm		
	Dielectric 1	FR-4	Dielectric		0.2028mm	4.4	
4	Gnd	CF-003	Signal	1/2oz	0.01801mm		
	Dielectric 3	PP-006	Prepreg		0.4mm	4.4	0.02
5	Routing	CF-003	Signal	1/2oz	0.01801mm		
	Dielectric 5	PP-006	Prepreg		0mm	4.4	0.02
6	Bottom_Gnd	CF-004	Signal	1oz	0.035mm		
	Bottom Solder	Solder Resist	Solder Mask		0.01016mm	4.4	
	Bottom Overlay		Overlay				

Fig: Used Layer Stack Up

7.3 Key Concepts

Throughout this project, we gained knowledge and practical experience in several advanced PCB design concepts:

- **Impedance Matching**: Ensuring that the impedance of the traces matched the components to minimize signal reflection and power loss.
- **Via Stitching and Shielding:** Techniques to enhance signal integrity and reduce electromagnetic interference by strategically placing vias.
- **Teardrops**: Adding teardrops at trace-to-pad junctions to improve mechanical strength and electrical performance.
-



- **Controlling Impedance in Altium**: Learning how to manage and control impedance across different layers using Altium Designer.
- **Defining Impedance Profiles in Altium**: Setting up and utilizing impedance profiles to ensure consistent signal performance across the PCB.

	Top Ref	Bottom Ref	Width (W1)	Impe...	Devia...	Delay...
✓		2 - RF_Grou...	0.36542mm	50.01	0.02%	6.1009...
✓	1 - Top Layer	3 - Power	0.22465mm	50	0.01%	7.0451...
✓	2 - RF_Grou...	4 - Gnd	0.21842mm	49.99	0.02%	7.0463...
✓	3 - Power	5 - Routing	0.21842mm	49.99	0.02%	7.0463...
✓	4 - Gnd	6 - Bottom_...	0.08189mm		0.03%	
✓	5 - Routing		0.10733mm		0.01%	

Fig: Single 50Ohm Impedance Profile

	Top Ref	Bottom Ref	Width (W1)	Trace Gap...	Impe...	Devia...	Delay...
✓		2 - RF_Grou...	0.17235mm	0.127mm	100.01	0.01%	5.6428...
✓	1 - Top Layer	3 - Power	0.10424mm	0.127mm	100.02	0.02%	7.0775...
✓	2 - RF_Grou...	4 - Gnd	0.10321mm	0.127mm	99.96	0.04%	7.0781...
✓	3 - Power	5 - Routing	0.10321mm	0.127mm	99.96	0.04%	7.0781...
✓	4 - Gnd	6 - Bottom_...	0.00876mm	0.127mm	100.01	0.01%	6.7709...
✓	5 - Routing		0.07754mm	0.127mm		0.01%	

Fig: Differential 100Ohm Impedance Profile

7.4 Layout Details

The PCB is a multi-layer design with specific functionalities assigned to each layer to optimize performance and minimize interference.

- **Top Layer**:
    - All components and almost all interconnections are located on the top layer (Figure 22).
    - Impedance-controlled RF traces (single-ended 50 Ω CBCPW and differential 100 Ω traces) are situated here.
    - Direct connection of all component ground terminals to the surrounding GND plane without thermal relief connections ensures optimal grounding.

- **RF Ground Layer**:
    - Positioned directly below the top layer to support the 50 Ω and 100 Ω waveguide traces.
    - The solid and uninterrupted nature of this layer is critical for providing a direct path for RF return currents, ensuring efficient signal transmission.

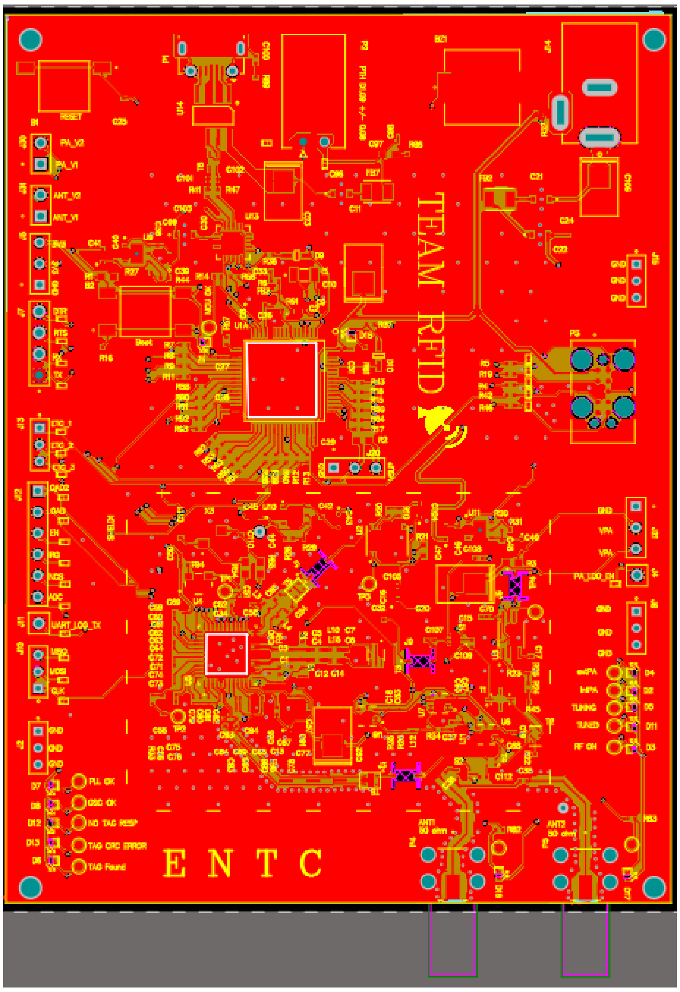


Fig: Top Layer

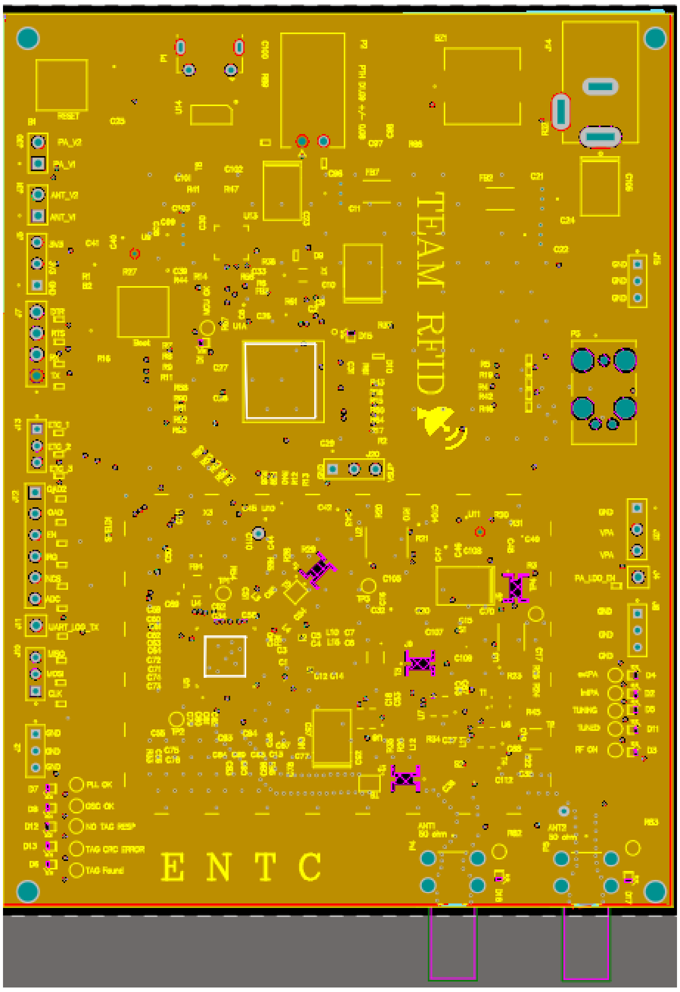


Fig: RF Ground Layer

- **Power Layer**:
    - Utilized primarily for distributing supply voltages through power planes, with minimal traces to avoid interference.

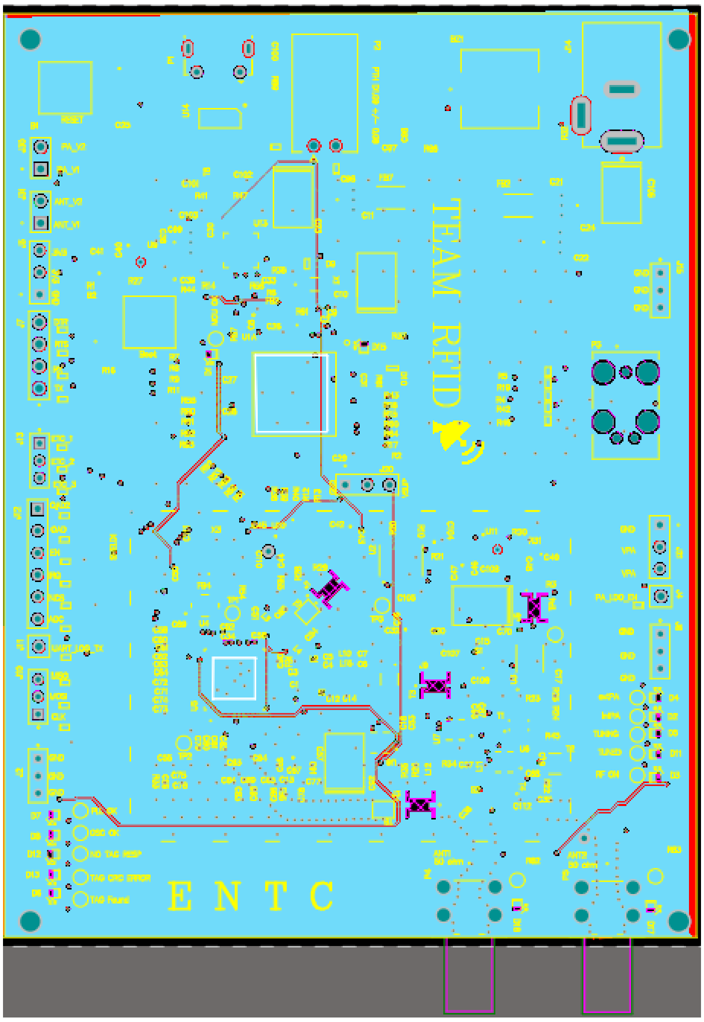


Fig: Power Layer

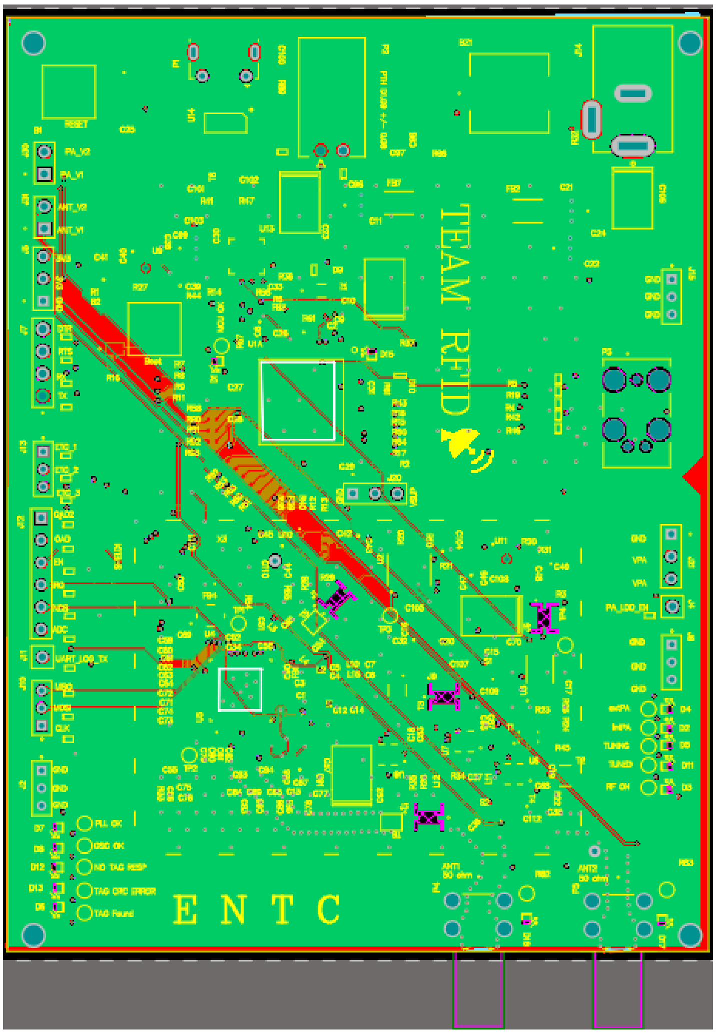


Fig: Power Ground Layer

- **Routing Layer**:
    - Dedicated to interconnecting components while minimizing cross-talk effects on RF traces.

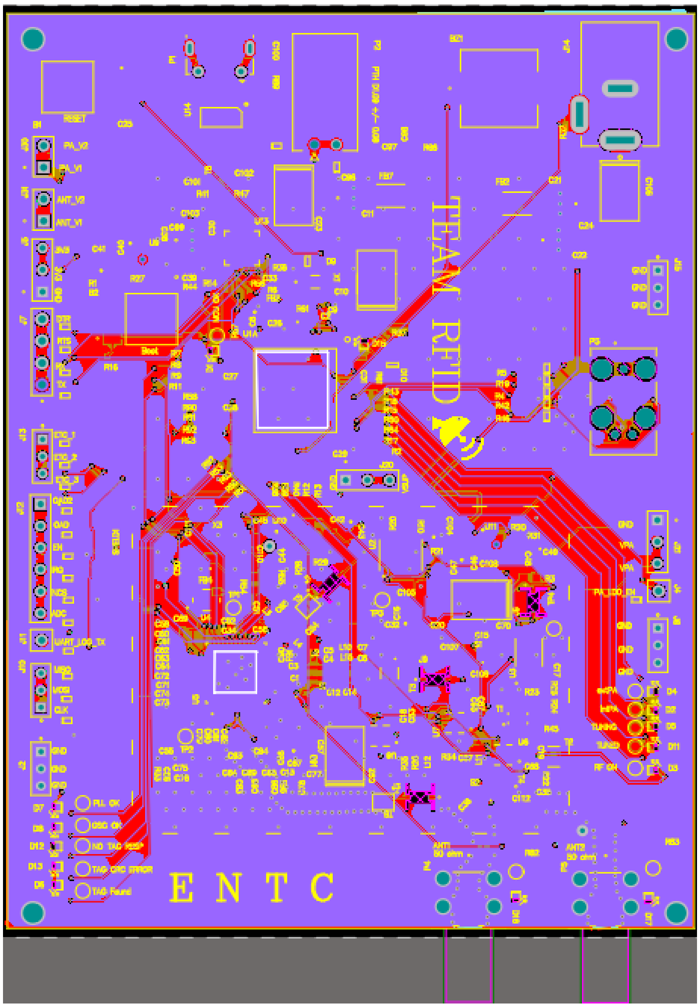


Fig: Routing Layer

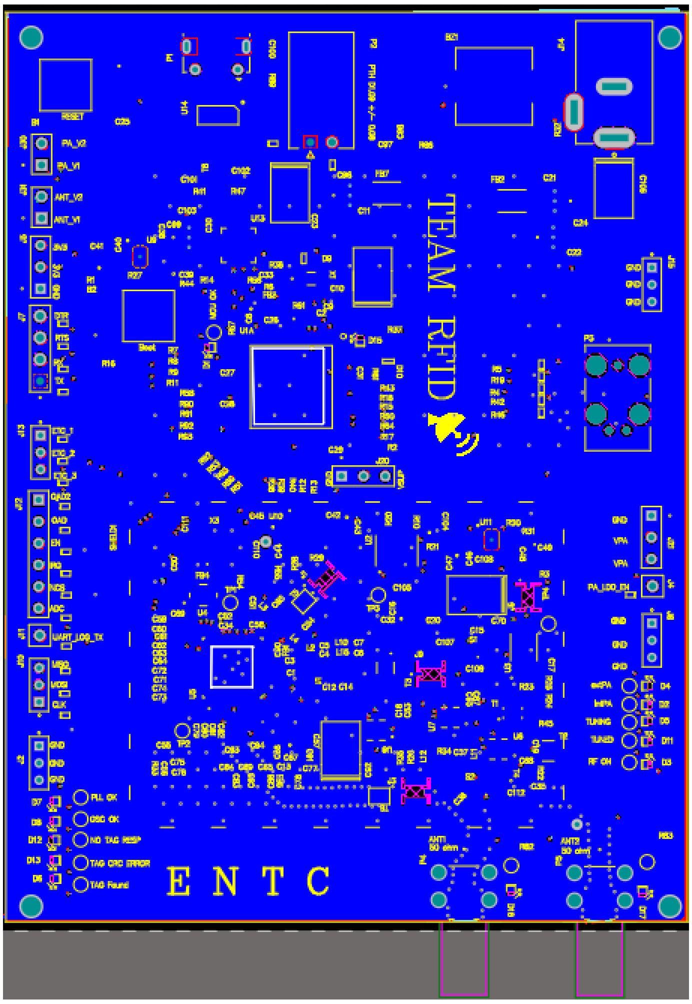


Fig: Bottom Ground Layer

7.5 PCB Specifications

- **Material**: FR4
- **Thickness**: 1.6mm
- **Surface Finish**: ENIG (Electroless Nickel Immersion Gold)
- **Copper Weight**: 1 oz for outer layers, 0.5 oz for inner layers

Bare PCB

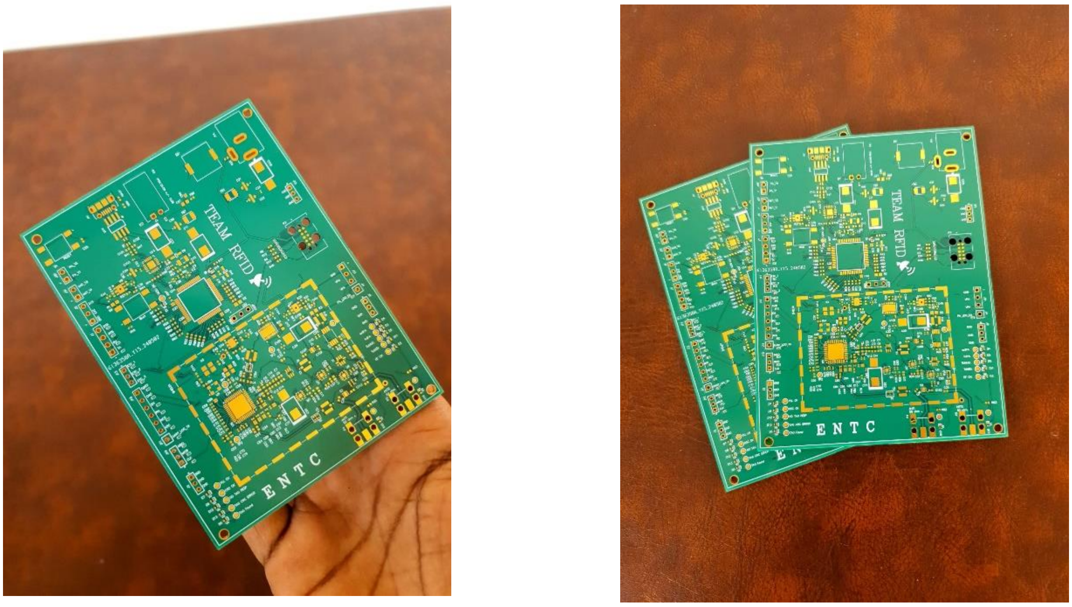


Fig: Fabricated PCB

7.6 Additional Details

The PCB includes RF circuitry designed to support tuning the radio frequency from 840 to 960 MHz. Two SMB antenna connectors are available for controlled scanning. The external power amplifier requires a 6V power adapter when the external PA TX option is used. Numerous test points are available for easy access and measurement, allowing modifications such as controlling RF circuitry with an external MCU or bypassing the on-board power amplifier.

The PCB was fabricted by JLC PCB. (https://jlcpcb.com/)

7.7 Conclusion

This project provided a comprehensive learning experience in PCB design, from cost-effective layer stackup selection to advanced impedance control techniques. The practical skills and knowledge gained will be invaluable for future projects in the RF and microwave engineering field.

8 Bill of Materials

Digikey

Designator	Description	Quantity
B1	Non-Open Push-Button 0.1A 24V	1
B2	Non-Open Push-Button 0.1A 24V	1
BZ1	AUDIO PIEZO TRANSDUCER 12.5V SMD	1
C1, C3	CAP CER 1.2PF 50V NP0 0402	2
C2, C8, C16, C39, C41, C43, C45, C47, C49, C91, C104	CAP FEEDTHRU 0.47UF 6.3V 0603	11
C4, C5	CAP CER 15PF 50V NP0 0402	2
C6, C7	CAP CER 5.6PF 50V NP0 0402	2
C9, C10	CAP CER 4.7PF 100V NP0 0402	2
C11, C20, C92	CAP POLYMER 10UF 20% 16V SMD	3
C12, C14, C53, C57, C58, C60, C62, C64, C68, C70, C76, C95	CAP CER 120PF 50V C0G/NP0 0201	12
C13, C15, C18, C19, C26, C30, C33, C52, C59, C61, C63, C66, C71, C73, C75, C78, C84, C85, C87, C89, C90, C105	CAP CER 2.2UF 6.3V X5R 0201	22
C17	CAP CER 2.2NF 50V X7R 0402	1
C23	CAP ALUM POLY 6.8UF 20% 16V SMD	1
C25, C50	CAP CER 0.1UF 16V X7R 0402	2
C27, C28, C29, C31, C67, C69, C77, C83, C86, C88, C98	CAP CER 0.1UF 6.3V X6S 0204	11
C32, C35, C36, C54, C65, C93, C94, C107, C108, C109, C112	CAP CER 82PF 50V C0G/NP0 0402	11
C34, C72, C74	CAP CER 30PF 50V C0G/NP0 0201	3
C37	CAP CER 3.6PF 50V C0G/NP0 0402	1
C38, C40, C42, C44, C46, C48	CAP CER 2.2UF 6.3V X5R 0402	6
C51	CAP CER 0.22UF 35V X5R 0402	1
C55	CAP CER 3900PF 10V U2J 0402	1
C56	CAP CER 150PF 50V NP0 0402	1
C79, C80, C81, C82	CAP CER 10000PF 10V X7R 0201	4
C96, C99	CAP FEEDTHRU 1UF 20% 10V 0805	2
C97	CAP CER 4.7UF 10V X5R 0603	1
C100	CAP CER 4PF 50V C0G/NP0 0402	1
C101, C102	CAP CER 47PF 50V NP0 0402	2
C103	CAP CER 0.1UF 6.3V X6S 0201	1
C110, C111	CAP CER 11PF 50V C0G/NP0 0402	2
D1, D2, D3, D4, D5, D6, D7, D8, D11, D16, D17	LED BLUE 0402 SMD	11
D9, D10	DIODE SCHOTTKY 10V 3A SOD323	2
D12, D13, D15	LED RED 0402 SMD	3
D20, D21, D22, D23, D24, D25, D26, D27, D28, D29, D30, D31, D32, D33, D34, D35, D36, D37, D38, D39, D40, D41, D42, D43, D44, D45, D47, D48, D49, D50, D52	TVS DIODE 3VWM 17VC ST0201	31
FB1	FERRITE BEAD 330 OHM 0402 1LN	1
FB3, FB4, FB5	FERRITE BEAD 1 KOHM 0402 1LN	3
FB7	FERRITE BEAD 31 OHM 2SMD 1LN	1
J1	CONN COAX JACK STR 50 OHM SMD	1
J3, J6, J9	CONN COAX JACK STR 50 OHM SMD	3
L1, L2, L3, L4	FIXED IND 30NH 270MA 580 MOHM	4
L10, L15	FIXED IND 3.6NH 900MA 40 MOHM	2
L11	FIXED IND 6.8NH 700MA 90 MOHM	1

L12	Inductor RF Chip Wirewound 5.6nH 0.2nH 100MHz 30Q-Factor 800mA 51mOhm DCR 0402 T/R	1
P1	Micro USB Connector	1
P2	Header, 2-Pin, Right Angle	1
P4, P5	CONN SMB JACK STR 50OHM EDGE MNT	2
R1, R2, R3	RES SMD 0.0OHM JUMPER 1/10W 0603	3
R4, R5, R14, R15, R17, R18, R19, R42, R46, R50, R51, R52, R53, R64, R65, R66, R81, R82, R83	RES SMD 220 OHM 5% 1/16W 0402	19
R6, R7, R8, R9, R10, R11, R12, R13, R20, R34, R36, R37, R38, R39, R40, R43, R56, R57, R58, R89	RES SMD 0.0OHM JUMPER 1/16W 0402	20
R16, R27, R29, R31, R61	RES SMD 10K OHM 1% 1/16W 0402	5
R21	RES SMD 100 OHM 1% 1/16W 0402	1
R22	RES SMD 51.1 OHM 1% 1/16W 0402	1
R23	RES SMD 52R3 1% 0.1W 0402	1
R24	RES SMD 249 OHM 1% 1/16W 0402	1
R25, R45	RES SMD 62 OHM 1% 1/16W 0402	2
R26	Res Thick Film 0402 75 Ohm 1% 0.1W(1/10W) ±100ppm/C Molded SMD Automotive Punched T/R	1
R28	RES SMD 35.7K OHM 1% 1/16W 0402	1
R30	RES SMD 42.2K OHM 1% 1/10W 0402	1
R33	RES SMD 15K OHM 5% 1/10W 0402	1
R41, R47	RES SMD 27 OHM 1% 1/16W 0402	2
R44	RES SMD 31.6K OHM 1% 1/16W 0402	1
R86	RES SMD 20 OHM 5% 1/16W 0402	1
S1, S2	IC SWITCH SP2T	2
SHIELD1	RF Shield 51.1 x 38.4 x 6.5	1
T1	FILTER LOWPASS 863-960MHZ	1
T2	COUPLER 20DB 1700-2200MHZ 0805	1
T3	1:1 BALUN- 900MHZ 50/50 Ohm	1
T4	Directional Coupler	1
T5, T6	XFRMR BALUN RF 800-1000MHZ 0805	2
T8	CHOKE COM MODE 90 OHM .37A SMD	1
U1	IC MCU 32BIT 1MB FLASH 64LQFP	1
U2	699 – 960 MHz 2-stage Power Amplifier	1
U3	IC LOG AMP RF DETECT 45DB 8-MSOP	1
U4	OSC TCXO 20.0000MHZ CLP SW SMD	1
U5	UHF EPC CLASS1 GEN2 READER	1
U6, U7, U8	IC RF DTC 100-3000MHZ 10QFN	3
U9, U10, U11	IC REG LDO ADJ 1A 6DFN	3
U13	IC USB SERIAL FULL UART 20QFN	1
U14	TVS DIODE 5.25VWM 8SOIC	1
X1	CRYSTAL 32.7680KHZ 6PF SMD	1
X3	CRYSTAL 20.0000MHZ 7.2PF SMD	1
B1	Non-Open Push-Button 0.1A 24V	1
B2	Non-Open Push-Button 0.1A 24V	1
BZ1	AUDIO PIEZO TRANSDUCER 12.5V SMD	1
C1, C3	CAP CER 1.2PF 50V NP0 0402	2
C2, C8, C16, C39, C41, C43, C45, C47, C49, C91, C104	CAP FEEDTHRU 0.47UF 6.3V 0603	11
C4, C5	CAP CER 15PF 50V NP0 0402	2
C6, C7	CAP CER 5.6PF 50V NP0 0402	2
C9, C10	CAP CER 4.7PF 100V NP0 0402	2
C11, C20, C92	CAP POLYMER 10UF 20% 16V SMD	3
C12, C14, C53, C57, C58, C60, C62, C64, C68, C70, C76, C95	CAP CER 120PF 50V C0G/NP0 0201	12

C13, C15, C18, C19, C26, C30, C33, C52, C59, C61, C63, C66, C71, C73, C75, C78, C84, C85, C87, C89, C90, C105	CAP CER 2.2UF 6.3V X5R 0201	22
C17	CAP CER 2.2NF 50V X7R 0402	1
C23	CAP ALUM POLY 6.8UF 20% 16V SMD	1
C25, C50	CAP CER 0.1UF 16V X7R 0402	2
C27, C28, C29, C31, C67, C69, C77, C83, C86, C88, C98	CAP CER 0.1UF 6.3V X6S 0204	11
C32, C35, C36, C54, C65, C93, C94, C107, C108, C109, C112	CAP CER 82PF 50V C0G/NP0 0402	11
C34, C72, C74	CAP CER 30PF 50V C0G/NP0 0201	3
C37	CAP CER 3.6PF 50V C0G/NP0 0402	1
C38, C40, C42, C44, C46, C48	CAP CER 2.2UF 6.3V X5R 0402	6
C51	CAP CER 0.22UF 35V X5R 0402	1
C55	CAP CER 3900PF 10V U2J 0402	1
C56	CAP CER 150PF 50V NP0 0402	1
C79, C80, C81, C82	CAP CER 10000PF 10V X7R 0201	4
C96, C99	CAP FEEDTHRU 1UF 20% 10V 0805	2
C97	CAP CER 4.7UF 10V X5R 0603	1
C100	CAP CER 4PF 50V C0G/NP0 0402	1
C101, C102	CAP CER 47PF 50V NP0 0402	2
C103	CAP CER 0.1UF 6.3V X6S 0201	1
C110, C111	CAP CER 11PF 50V C0G/NP0 0402	2
D1, D2, D3, D4, D5, D6, D7, D8, D11, D16, D17	LED BLUE 0402 SMD	11
D9, D10	DIODE SCHOTTKY 10V 3A SOD323	2
D12, D13, D15	LED RED 0402 SMD	3
D20, D21, D22, D23, D24, D25, D26, D27, D28, D29, D30, D31, D32, D33, D34, D35, D36, D37, D38, D39, D40, D41, D42, D43, D44, D45, D47, D48, D49, D50, D52	TVS DIODE 3VWM 17VC ST0201	31
FB1	FERRITE BEAD 330 OHM 0402 1LN	1
FB3, FB4, FB5	FERRITE BEAD 1 KOHM 0402 1LN	3
FB7	FERRITE BEAD 31 OHM 2SMD 1LN	1
J1	CONN COAX JACK STR 50 OHM SMD	1
J3, J6, J9	CONN COAX JACK STR 50 OHM SMD	3
L1, L2, L3, L4	FIXED IND 30NH 270MA 580 MOHM	4
L10, L15	FIXED IND 3.6NH 900MA 40 MOHM	2
L11	FIXED IND 6.8NH 700MA 90 MOHM	1
L12	Inductor RF Chip Wirewound 5.6nH 0.2nH 100MHz 30Q-Factor 800mA 51mOhm DCR 0402 T/R	1
P1	Micro USB Connector	1
P2	Header, 2-Pin, Right Angle	1
P4, P5	CONN SMB JACK STR 50OHM EDGE MNT	2
R1, R2, R3	RES SMD 0.0OHM JUMPER 1/10W 0603	3
R4, R5, R14, R15, R17, R18, R19, R42, R46, R50, R51, R52, R53, R64, R65, R66, R81, R82, R83	RES SMD 220 OHM 5% 1/16W 0402	19
R6, R7, R8, R9, R10, R11, R12, R13, R20, R34, R36, R37, R38, R39, R40, R43, R56, R57, R58, R89	RES SMD 0.0OHM JUMPER 1/16W 0402	20
R16, R27, R29, R31, R61	RES SMD 10K OHM 1% 1/16W 0402	5
R21	RES SMD 100 OHM 1% 1/16W 0402	1
R22	RES SMD 51.1 OHM 1% 1/16W 0402	1
R23	RES SMD 52R3 1% 0.1W 0402	1
R24	RES SMD 249 OHM 1% 1/16W 0402	1

R25, R45	RES SMD 62 OHM 1% 1/16W 0402	2
R26	Res Thick Film 0402 75 Ohm 1% 0.1W(1/10W) ±100ppm/C Molded SMD Automotive Punched T/R	1
R28	RES SMD 35.7K OHM 1% 1/16W 0402	1
R30	RES SMD 42.2K OHM 1% 1/10W 0402	1
R33	RES SMD 15K OHM 5% 1/10W 0402	1
R41, R47	RES SMD 27 OHM 1% 1/16W 0402	2
R44	RES SMD 31.6K OHM 1% 1/16W 0402	1
R86	RES SMD 20 OHM 5% 1/16W 0402	1
S1, S2	IC SWITCH SP2T	2
SHIELD1	RF Shield 51.1 x 38.4 x 6.5	1
T1	FILTER LOWPASS 863-960MHZ	1
T2	COUPLER 20DB 1700-2200MHZ 0805	1
T3	1:1 BALUN- 900MHZ 50/50 Ohm	1
T4	Directional Coupler	1
T5, T6	XFRMR BALUN RF 800-1000MHZ 0805	2
T8	CHOKE COM MODE 90 OHM .37A SMD	1
U1	IC MCU 32BIT 1MB FLASH 64LQFP	1
U2	699 – 960 MHz 2-stage Power Amplifier	1
U3	IC LOG AMP RF DETECT 45DB 8-MSOP	1
U4	OSC TCXO 20.0000MHZ CLP SW SMD	1
U5	UHF EPC CLASS1 GEN2 READER	1
U6, U7, U8	IC RF DTC 100-3000MHZ 10QFN	3
U9, U10, U11	IC REG LDO ADJ 1A 6DFN	3
U13	IC USB SERIAL FULL UART 20QFN	1
U14	TVS DIODE 5.25VWM 8SOIC	1
X1	CRYSTAL 32.7680KHZ 6PF SMD	1
X3	CRYSTAL 20.0000MHZ 7.2PF SMD	1

9 Enclosure Design

9.1 SolidWorks Design

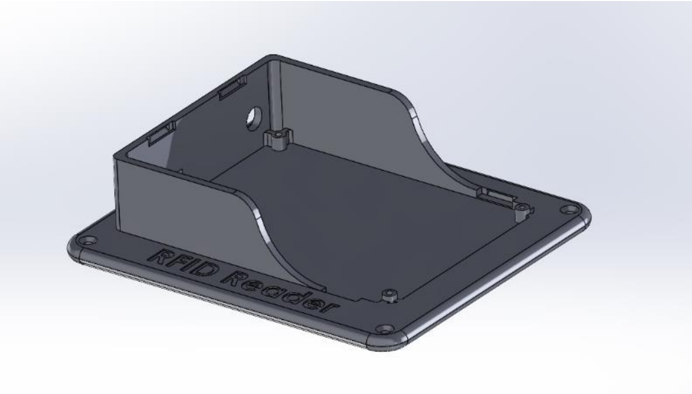


Fig: Box

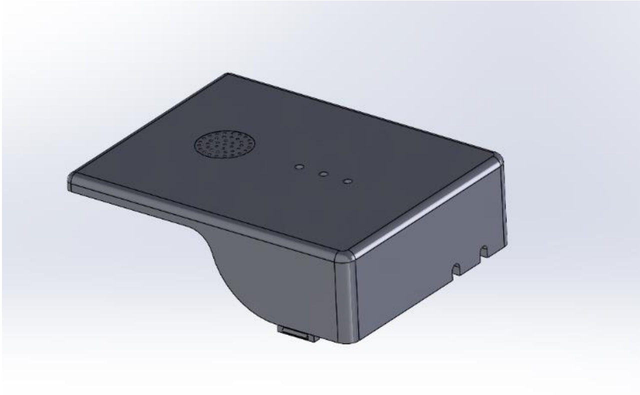


Fig: Lid

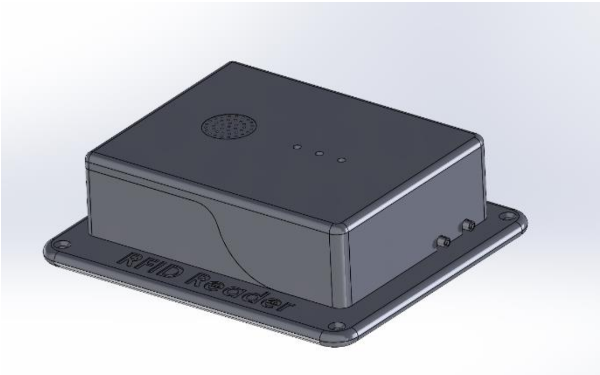


Fig: Assembly

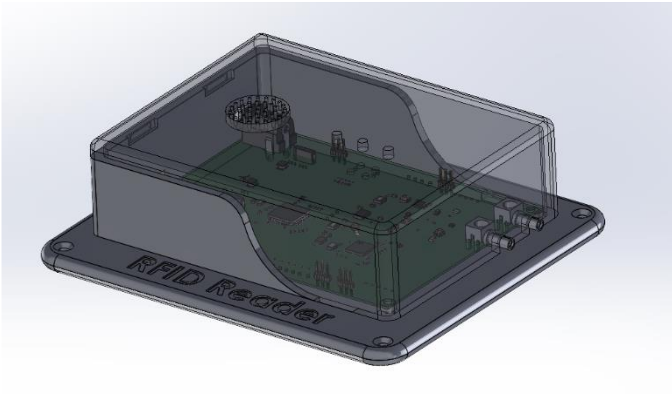


Fig: Assembly

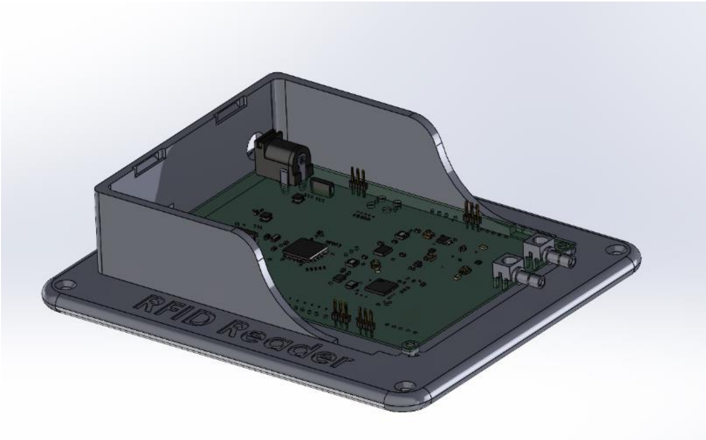


Fig: Assembly

10.2 Printed Enclosure

Fig: Box

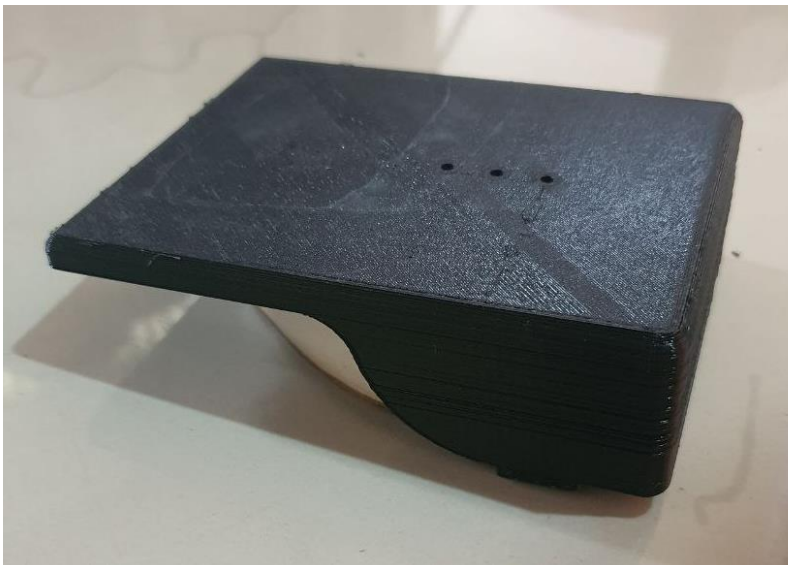


Fig: Lid

Fig: Assembly

Fig: Assembly

10 Antenna Design

10.1 Introduction

The antenna design for the RFID project is a critical component that ensures efficient signal transmission and reception. Initially, we considered purchasing a ready-made antenna, but due to the high cost and my curiosity about antenna design, we decided to design our own. We designed several antennas with a focus on size and gain for operation at 915 MHz. This section outlines the design process, key considerations, and technical decisions involved in developing an effective antenna system for our RFID reader.

10.2 Basic equations and theory used

While designingng the antennas we initialyy tried to achive the required parameters such as gain return-loss coeffiecient using the microstrip antenna. As it did not bare the expected results we designed some PIFA antennas due to their smaller size and polularity in modern day deivces.

10.2.1 Microstrip Patch Antennas

Patch antennas are simple to design on the surface layer of a PCB and they obey two simple design rules:

1. Patch antennas are placed over a ground plane, and the ground plane should extend well beyond the edges of the antenna
2. The width of a patch antenna is sized to support a standing wave resonance between the patch and the ground plane

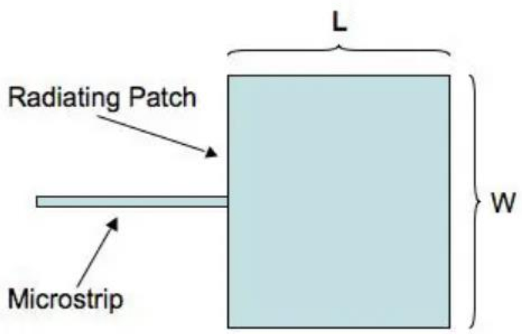


Fig: Simple Patch Antenna

The following set of equations can be used to design a patch antenna on a PCB. The only required inputs are the PCB laminate material dielectric constant, the layer thickness, and the frequency of operation. There will be an effective dielectric constant that determines the requried length of the patch antenna, as well as the relation between geometry and operating frequency.

To start, select an operating frequency and dielectric constant for the PCB substrate material, and calculate the required width of the patch antenna.

$$W = \frac{c}{2f_o\sqrt{\frac{\varepsilon_R+1}{2}}}$$

Next, use this value to calculate the effective dielectric constant using the thickness of the PCB laminate (distance to the ground plane):

$$\varepsilon_{eff} = \frac{\varepsilon_R+1}{2} + \frac{\varepsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right]$$

Finally, use the above results to calculate the required length of the patch antenna:

$$L = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)}\right)$$

$$L^* = L + 0.824h\left(\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)}\right) = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}}$$

There are three different types of feeding methods: Direct, Coaxial, and Inset.

In order to excite a patch antenna, or to collect the signal received by a patch antenna, the antenna will need a feeding method. There are three often-cited methods for applying a feedline:

1. Direct connection between a microstrip and the antenna with a quarter-wave transformer
2. Placing an inset for a microstrip feedline into the antenna
3. Connecting a coaxial probe into the antenna on the back side of the antenna

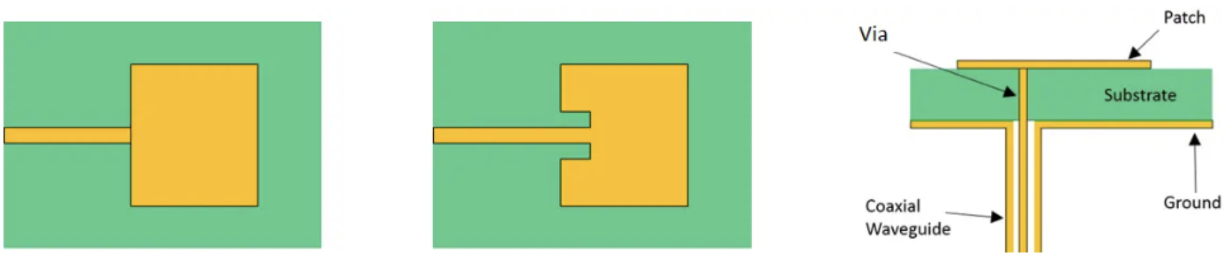


Fig: Patch antenna feedline with (left) direct feeding, (center) inset feeding, and (right) coaxial feeding.

Out of these methods we designed a patch antenna with a direct connection and a patch antenna with an inset feed. Below are some of the calculations we did for an antenna after considering the sybstrate as FR-4 and RT Druroid 5880.

Since we wanted our antenna to have a center frequency of 915MHz and a substrate hieght of 1.588mm, we have done the calculations for the width and length of the patch antenna, effective dielectric constant values and input impedences accordingly.

We had to use these calculated values and change them and the values slightly till we got the deisred results for our antenna.

$h = 0.1588\ \text{cm} \qquad f_r = 915\ \text{MHz}$

$\varepsilon_r = 4.4$ (FR4) $\qquad \varepsilon_r = 2.2$ (RT duroid 5880)

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{3\times10^8}{2\times 915\times10^6}\sqrt{\frac{2}{5.4}} = 9.977\ \text{cm}$$

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{3\times10^8}{2\times 915\times10^6}\sqrt{\frac{2}{3.2}} = 12.960\ \text{cm}$$

$$L = \lambda/2 = \frac{c_0/f_r}{2}$$

$$\varepsilon_{r\,eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{W}\right]^{-1/2}$$

$$\lambda_{eff} = \frac{c_{sub}}{f_r} = \frac{c_0/\sqrt{\varepsilon_{r\,eff}}}{f_r}$$

$$\varepsilon_{r\,eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{W}\right]^{-1/2}$$

$$= 2.7 + 1.7\,\frac{1}{\sqrt{1 + \frac{12\times0.1588}{9.977}}}$$

$$= 4.258$$

$$\varepsilon_{r\,eff} = 1.6 + 0.6 \times \frac{1}{\sqrt{1 + \frac{12\times0.1588}{12.96}}}$$

$$= 2.16$$

$$\Delta L = \frac{0.412h\,(\varepsilon_{r\,eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{r\,eff} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

$\Delta L = 0.0738\ \text{cm}$

$\Delta L = 0.1089\ \text{cm}$

$$L = \frac{c_0}{2 f_r \sqrt{\varepsilon_{r_{eff}}}} - 2\Delta L$$

$$L = \frac{3\times10^8}{2\times 915\times10^6\times\sqrt{2.16}} - 2\times 0.000738$$

$$= 11.007 \text{ cm}$$

$$L = \frac{3\times10^8}{2\times 915\times10^6\sqrt{4.258}} - 2\times 0.001089$$

$$= 7.727 \text{ cm}$$

$$Z_{in}\Big|_{edge} = 90\,\frac{\varepsilon_r^2}{\varepsilon_r - 1}\left(\frac{L}{W}\right)^2$$

$$Z_{in}\Big|_{edge} = 90\times\frac{4.258^2}{3.258}\left(\frac{7.727}{9.977}\right)^2$$

$$= 300.5726\ \Omega$$

$$Z_{in}\Big|_{edge} = 90\times\frac{2.16^2}{1.16}\times\left(\frac{11.007}{12.96}\right)^2$$

$$= 307.4368\ \Omega$$

$$Z_{in} = Z_{in}\Big|_{edge}\cos^2\left(\frac{\pi}{L}\times z_0\right)$$

$$50 = 300.5726\times\cos^2\left(\frac{\pi}{7.727}\times z_0\right)$$

$$\cos^{-1}\sqrt{\frac{50}{300.5726}}\times\frac{7.727}{\pi} = z_0$$

$$z_0 = 2.8302 \text{ cm}$$

$$\cos^{-1}\sqrt{\frac{50}{307.4368}} \times \frac{11.007}{\pi} = z_0$$

$$z_0 = 4.049 \text{ cm}$$

However as evident in the coming sections in this report the microstrip patch antenna deisgns did not yeild satisfactory resutls. Therefore, we opted to design and simulate PIFA antennas as well.

10.2.2 PIFA – Planar Inverterd F Antennas

The typical implementation of an inverted-F antenna is shown in the image below. This type of antenna is a quarter-wavelength antenna where the operational parameters (bandwidth, impedance, etc.) are set by adjusting the geometry along the quarter-wavelength leg of the antenna. An overview of a typical inverted-F antenna is shown below.

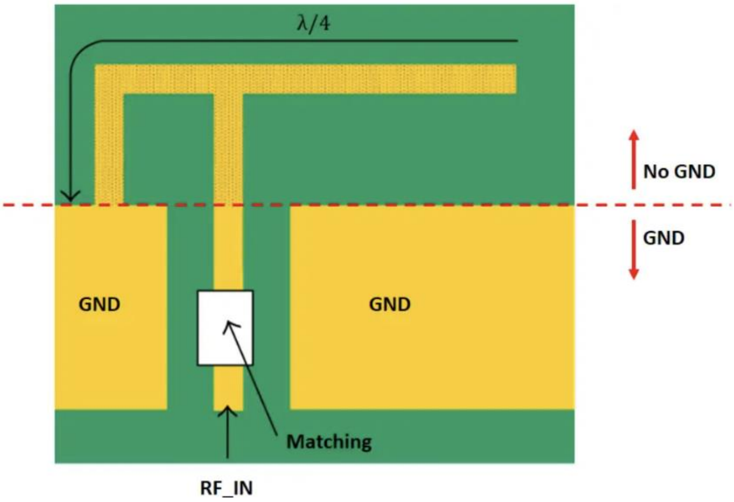


Fig: PIFA Antenna

The GND plane on L2 should run right to the edge of the GND on L1, and no copper pour should be below the antenna. This allows the antenna to radiate nearly omnidirectionally around the longer leg of the antenna where the current is non-zero. Although the radiation is omnidirectional and provided by fringing fields, this reduces the gain one would expect from this type of antenna. Thanks to their near omnidirectionality, these antennas were formerly the most popular for use as single-band or dual-band antennas in older mobile handsets.

Both of these antennas can be compared to patch antennas, and the inverted-F antenna (or its variants) offer several advantages over a basic patch antenna:

- Inverted-F antennas are smaller than patch antennas operating at the same wavelength
- Inverted-F antennas can be probe-fed or direct fed as long as a matching network is present
- Inverted-F antennas can be made multiband by applying more branches
- Inverted-F antenna bandwidths are comparable, but bandwidths can be more easily tuned with passives

The main disadvantage is the lower gain compared to a patch antenna because patch antennas emit into the half plane above the ground region. The other disadvantage is that you cannot form inverted-F antennas into groups as you would with a patch antenna array. Therefore, for more advanced antenna systems, patch antennas have dominated.

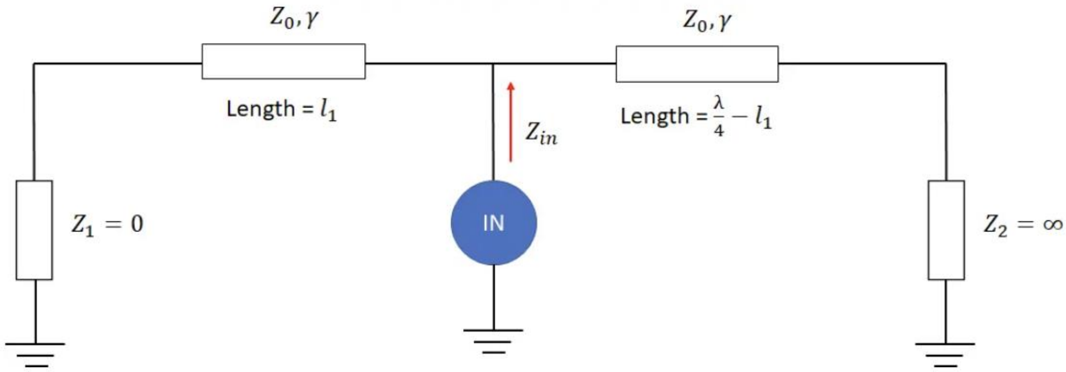
Unfortunately, there are no design equations for an inverted-F antenna due to its typically complex structure. However, because it is constructed from transmission lines, we can take a circuit-based approach to calculating the input impedance for a given microstrip width.

Although the characteristic impedance of the trace sections is difficult to determine, the propagation constant and total antenna length are easy to determine based on the quarter wavelength target and the target frequency:

$$\gamma = \frac{\omega\sqrt{\varepsilon_r}}{c_0}, L = \frac{c_0}{4f\sqrt{\varepsilon_r}}$$

In our instance the target frequency was 915MHz.

Once the propagation constant is known, the input impedance into the antenna can be calculated with a circuit model as long as the trace impedance is known. The circuit model below shows the two branches in the standard inverted-F antenna arrangement, where one leg is shorted (Z1 = 0 Ohms) and the other leg is open (Z2 = infinity).

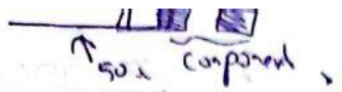


If you set these two legs in parallel and use the standard input impedance equation for each leg, you will find the following result for the antenna's input impedance:

$$Z_{in} = Z_0\left(\coth(\gamma l_1) + \tanh\left(\gamma\left(\frac{\lambda}{4} - l_1\right)\right)\right)^{-1}$$

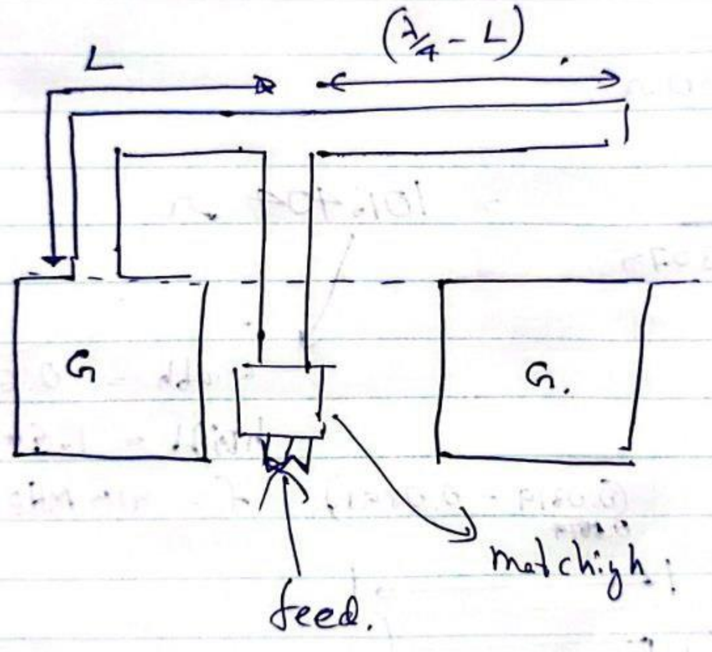
Therefore, unlike designing a patch antenna we did not have a starting point. But Ansys HFSS has a tool named "HFSS Antenna Toolkit" which synthesizes many types of antennas once the substrate height and material and the center frequency after given. Using this we synthesized a PIFA antenna using the substrate as FR-4. By method of trial and error we further improved it and reduced the antenna size by including two ground patches on the top layers as well.

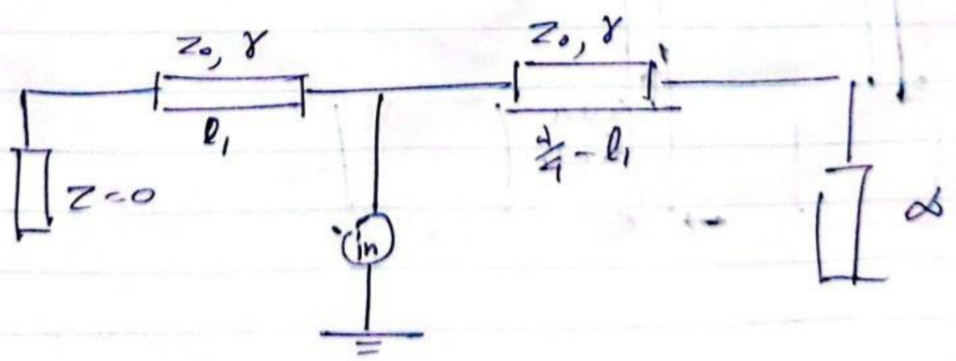
Below are some calculations we did for the Inverted F antenna design,



PIFA Antenn design : for 915 MHz.

$$\gamma = \frac{\omega\sqrt{\epsilon_r}}{C_0} \qquad L = \frac{C_0}{4f\sqrt{\epsilon_r}} = \text{length} = l_1$$





$$Z_{in} = Z_0 \left(\coth(\gamma l_1) + \tanh\left(\gamma\left(\frac{\lambda}{4} - l_1\right)\right)\right)^{-1}$$

$$l_1 = \frac{3\times10^8}{4\times915\times10^6\times\sqrt{4.4}} \qquad \gamma = \frac{2\pi\times915\times10^6\times\sqrt{4.4}}{3\times10^8}$$

$$l_1 = 0.0391\,m \qquad \gamma = 40.19.$$

$$Z_{in} = Z_0 \times 0.493075$$

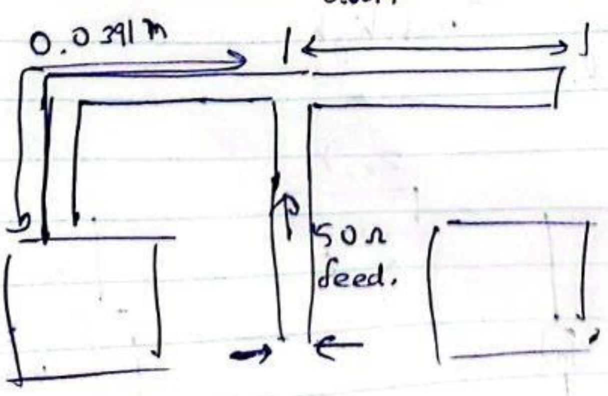
for Z_{in} to be $50\,\Omega$.

$$Z_0 = \frac{50}{0.493075} = 101.404\,\Omega$$

~~width = 0.625 mm~~
~~height = 1.6 mm~~
~~f = 915 MHz~~

because it is not a microstrip no bot...

$(0.0319 - 0.0391)$



Because there is not ground plane under the microstrip line we did not use this calculated microstrip line width. Instead we tested different widths in the simulation to get a fitting value

10.3 Antenna Selection and Design

We experimented with designing a few microstrip patch antennas, focusing on methods such as the inset feed method and a quarter-wave transformer. However, the gain remained negative, indicating a loss rather than a gain. After realizing the limitations of the microstrip antenna, we turned our attention to Planar Inverted-F Antennas (PIFA). We discovered that PIFA, Inverted-F Antennas (IFA), and Modified Inverted-F Antennas (MIFA) are commonly used in this frequency range.

10.4 Key Design Considerations

Several factors influenced the antenna design:

- **Frequency Range:** The antenna was designed to operate within the UHF RFID band, specifically from 840 to 960 MHz, to ensure compatibility with various RFID tags and systems.
- **Impedance Matching:** Achieving a proper impedance match (50 Ω) was crucial to minimize signal reflection and power loss, enhancing the overall system performance.
- **Antenna Gain:** A high-gain antenna was preferred to extend the read range and improve the reliability of tag detection.
- **Radiation Pattern:** A directional radiation pattern was selected to focus the signal strength in the desired direction, reducing interference and improving tag read accuracy.

10.5 Simulation and Optimization

We initially considered both Ansys HFSS and Cadence, model the antennas to predict their performance and make necessary adjustments. Since Ansys HFSS had a Student package which was free of charge we opted for that. The simulations helped us optimize parameters like the antenna's dimensions, substrate material, and feed point to achieve the desired frequency response and impedance characteristics.

10.6 Antennas Designed

We began by designing microstrip patch antennas due to their simplicity and ease of fabrication.

- **Design Methods:** We used methods such as the inset feed method and a quarter-wave transformer to feed the antennas.
- **Challenges:** Despite our efforts, the gain remained negative, indicating a loss rather than a gain. This was a significant limitation as it hindered the antenna's performance.
- **Simulation:** Using Ansys HFSS, we simulated the antennas to optimize their dimensions and feed points. However, the results consistently showed suboptimal performance.

10.6.1 Simple Patch Antenna

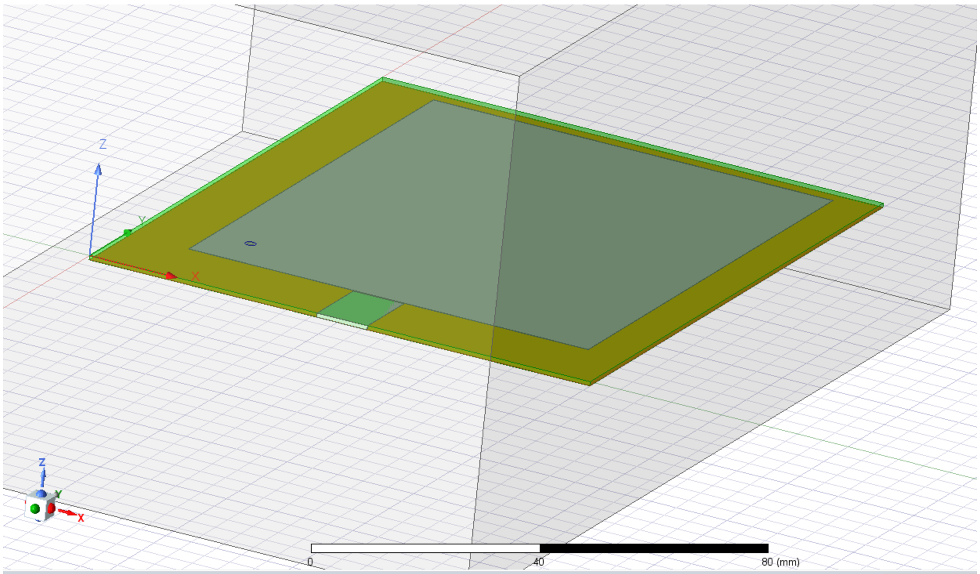


Fig: Simple Patch Antenna

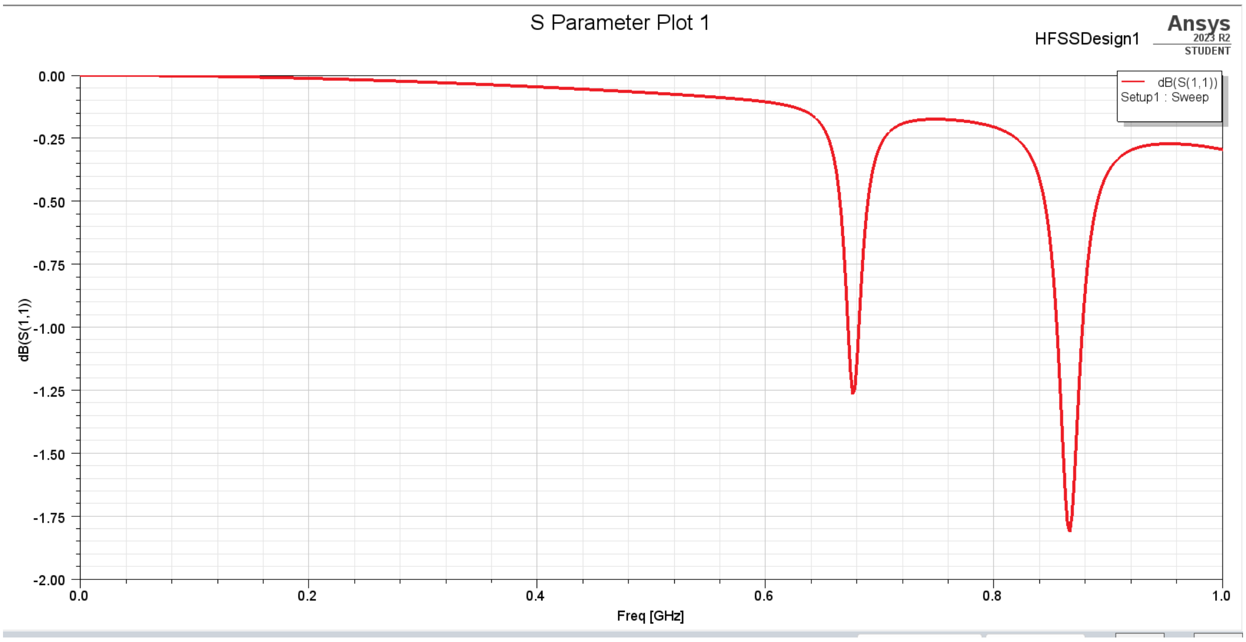


Fig: S Parameter Plot

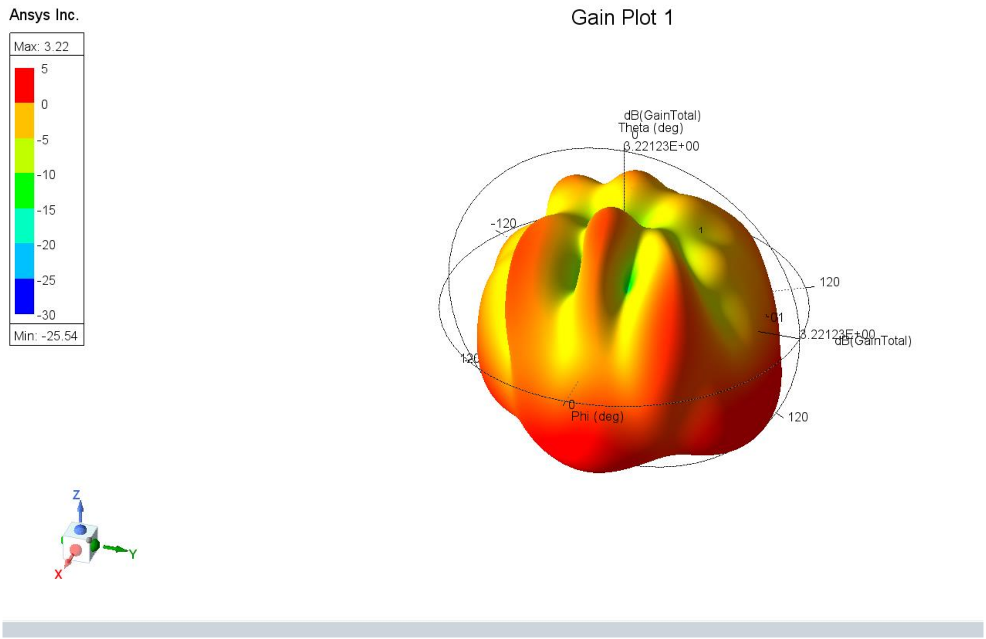


Fig: Gain Plot

- **Center frequency : 675MHz and 890Mhz**
- **Input reflection coefficient : -1.26 and -1.83**
- **Gain – 3.221E**

Outcome – While the gain was what we needed the center frequency did not have the desired dip at 915MHz and the S patameter values were much lower that -10dB which was what we required.

10.6.2 Microstrip Antenna with Inset Feed

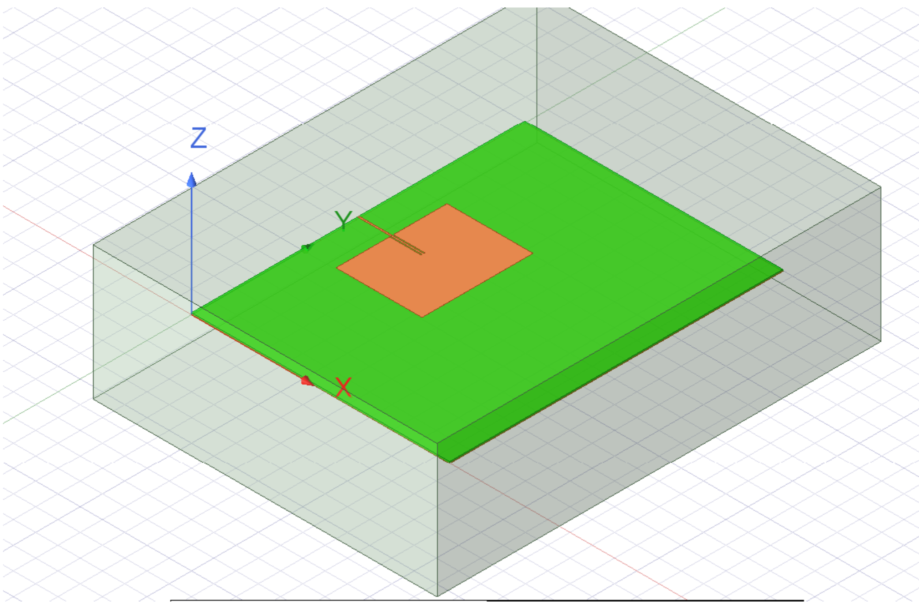


Fig: Microstrip Patch Antenna with Inset Feed

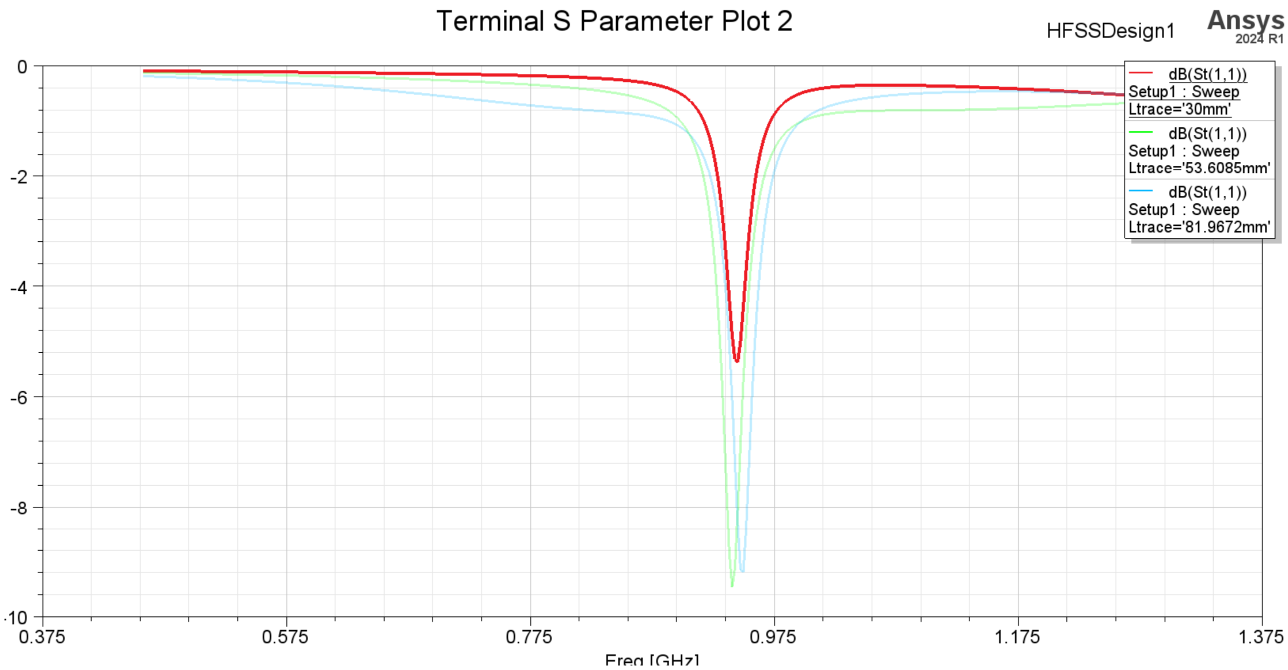


Fig: S Parameter Plot

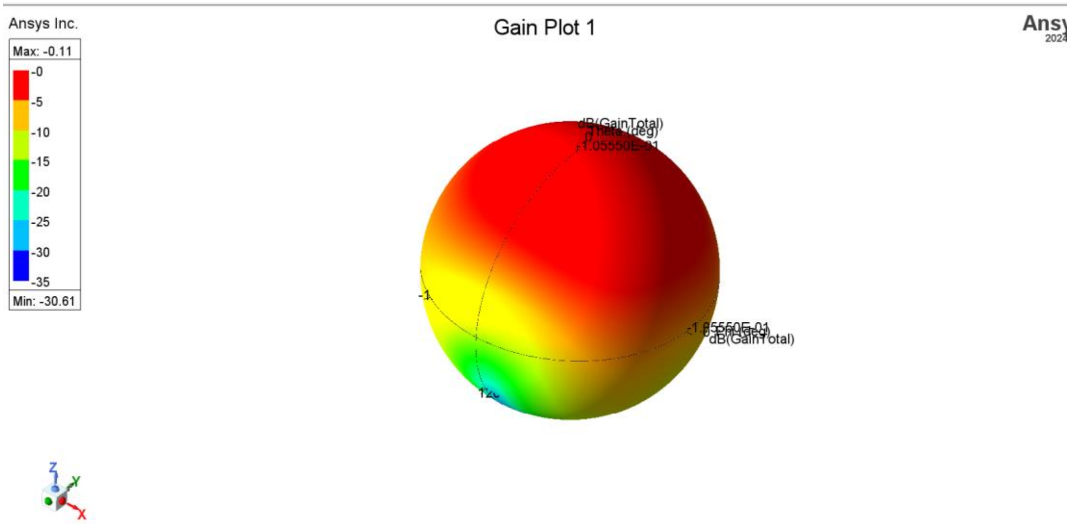


Fig: Gain Plot

- **Center frequency : 915Mhz**
- **Input reflection coefficient : -4.8**
- **Gain : -1.055E**

Outcome – While the center frequency was at the expected 915MHz, the S parameter value was below the dessired vaue of -10dB and it gave a loss rather than a gain.

Hence, we wanted to experiment with PIFA antennas.

10.5.3 PIFA- Planar Inverted F Antenna

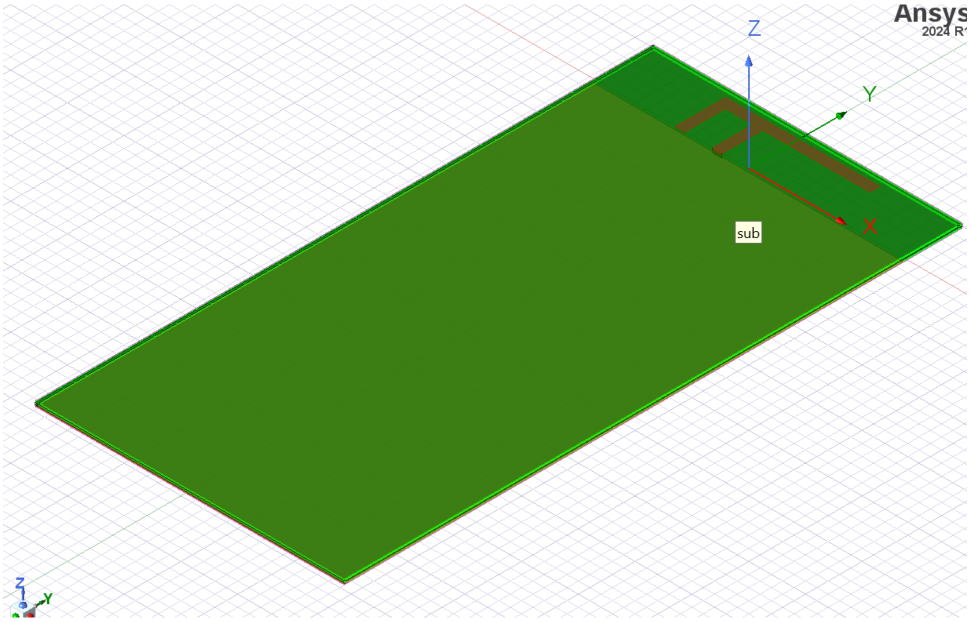


Fig: PIFA- Planar Inverted F Antenna

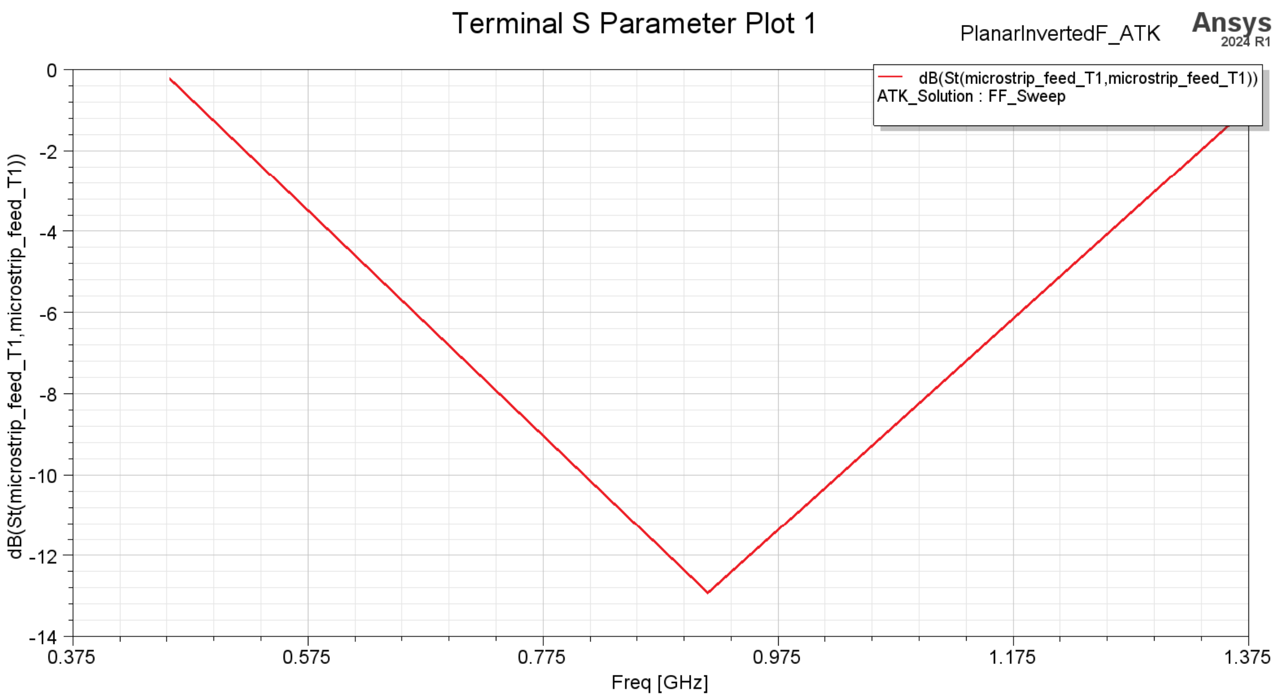


Fig: S Parameter Plot

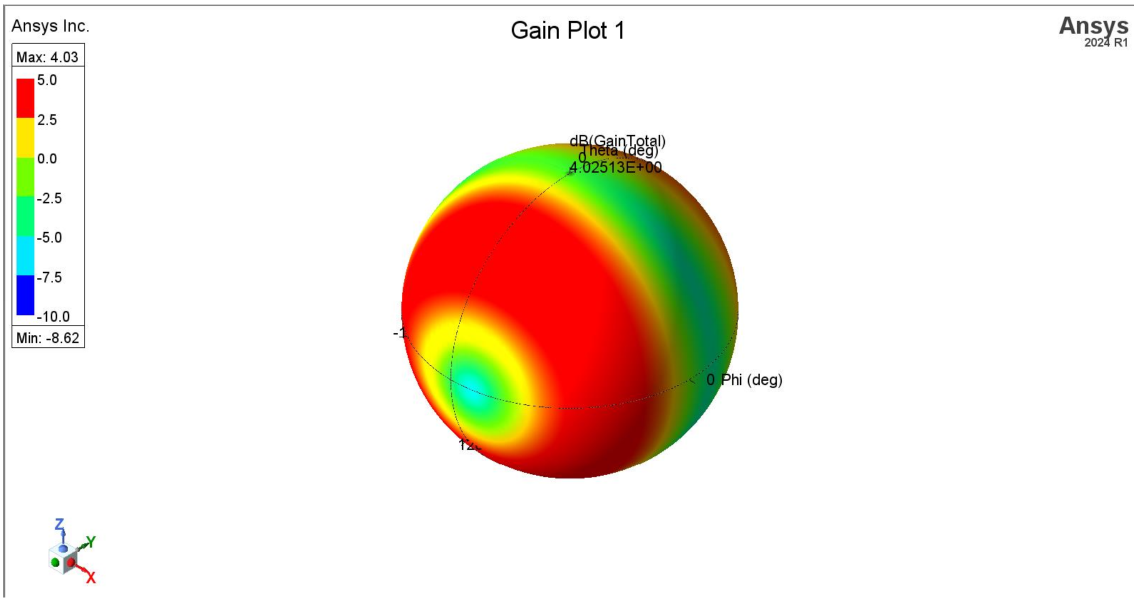


Fig: Gain Plot

- **Center frequency : 915Mhz**
- **Input reflection coefficient : -13.8**
- **Gain : 4.025E**

Outcome – While the center frequency was at the expected 915MHz and both the gain and S parameter were in the desired ranges we wanted to design a smaller sized antenna.

10.6.4 IFA- Inverted F Antenna

The IFA antenna has two ground patches on the Top Layer as well which are conntected to the Bottom Ground Plane using vias.

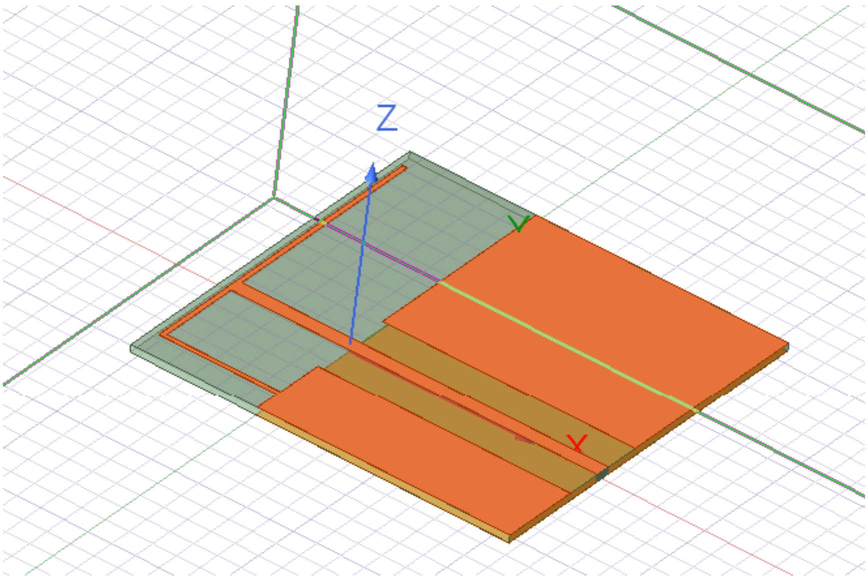


Fig: IFA- Inverted F Antenna

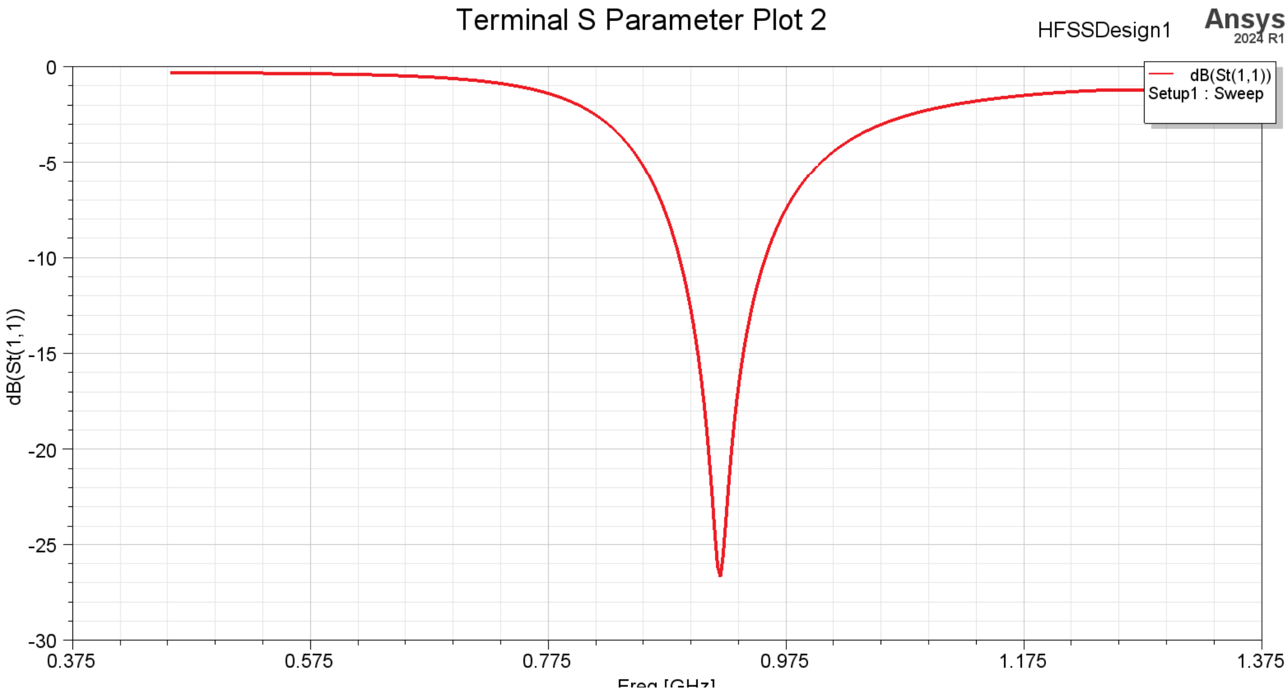


Fig: S Parameter Plot

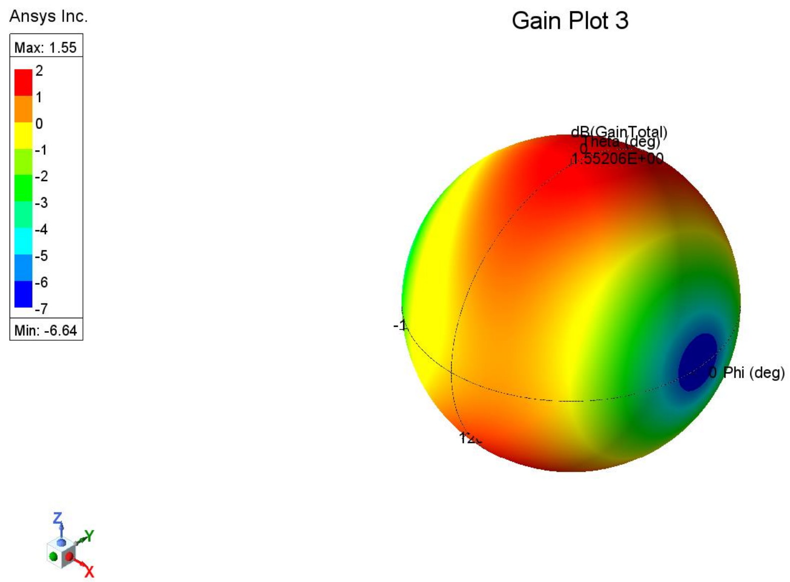


Fig: Gain Plot

- **Center frequency : 915Mhz**
- **Input reflection coefficient : -28.8**
- **Gain : 1.552E**

Outcome – All the requirements were in the desired ranges and we designed a smaller antenna. This is the final design we will use in the project.

10.7 Fabrication and Testing

The finalized design (IFA Antenna), will be fabricated using high-frequency PCB material to ensure low dielectric losses. We are using Altium Designer for this purpose. The antennas will be then integrated with the RFID reader PCB and tested in a controlled environment to validate their performance. Key performance metrics such as return loss, gain and radiation pattern will be measured to ensure compliance with the design specifications.

10.8 Anenna Specifications

- **Material**: FR4
- **Center Frequency:** 915MHz
- **Thickness**: 1.6mm
- **Antenna Material**: Copper
- **Antenna Size**: 8cm x 8cm

10.9 Integration with RFID Reader

The antenna was mounted on the PCB with careful consideration of its position and orientation to maximize performance. SMA connectors were used for easy connection and disconnection, allowing for quick adjustments and testing. The antenna's ground plane was also optimized to reduce interference and improve signal integrity.

10.10 Key Concepts

Throughout the antenna design process, several advanced concepts and practical skills were acquired:

- **Antenna Theory:** Understanding the fundamental principles of antenna operation, including impedance matching, radiation patterns, and gain.
- **Simulation Tools**: Proficiency in using Ansys HFSS for simulating and optimizing antenna designs.
- **Impedance Matching Techniques:** Applying techniques to achieve a 50 Ω impedance match, crucial for minimizing signal reflection and power loss.
- **Practical Testing:** Gaining hands-on experience in fabricating, integrating, and testing antennas to ensure they meet design specifications.

10.11 Final PCB Design of IFA – Inverted F Antenna

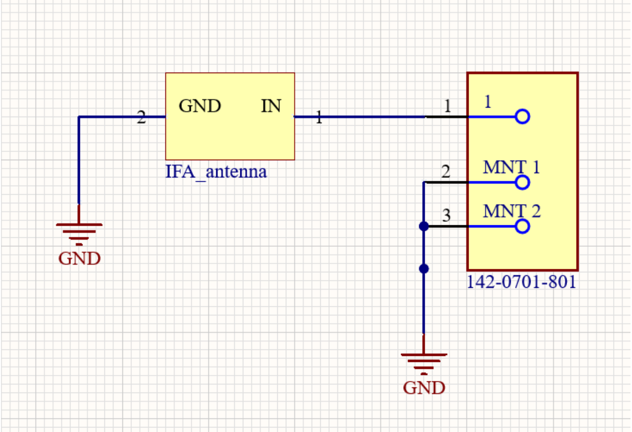


Fig: Schematic Diagram of the Antenna PCB

After finalizing the antenna design to our desired outputs, the design has been sent to JCLPCB for fabrication.

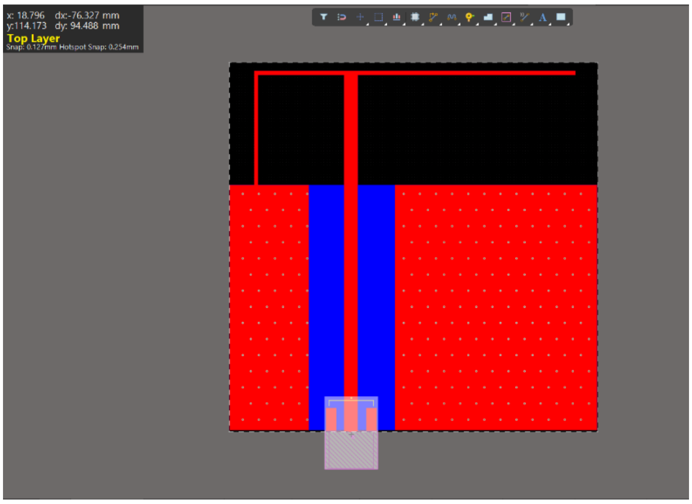


Fig: Top Layer of Antenna PCB

Fig: Multi Layer View

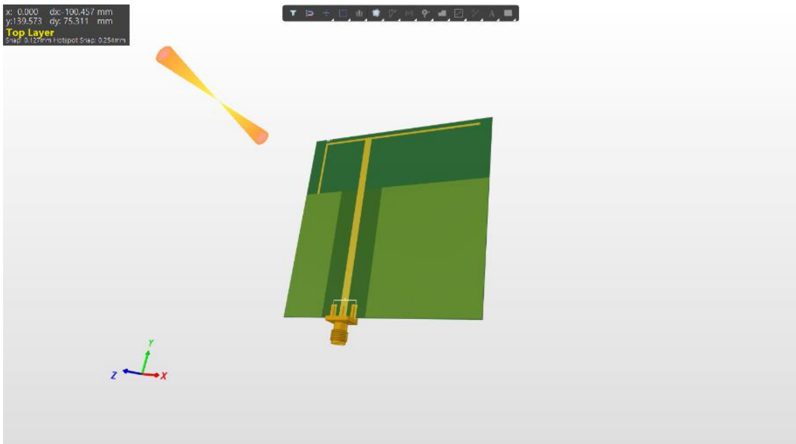


Fig: 3D View

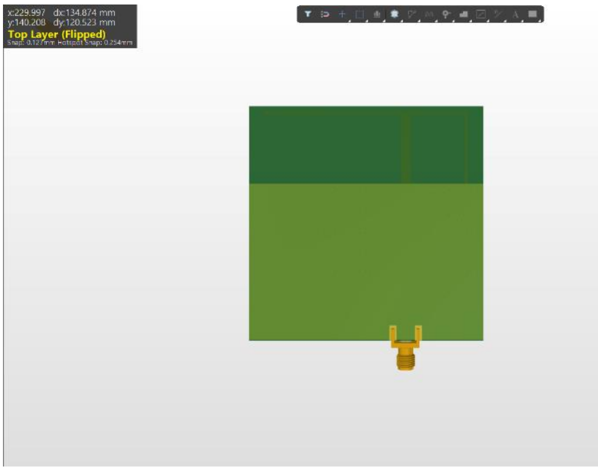


Fig: Bottom View

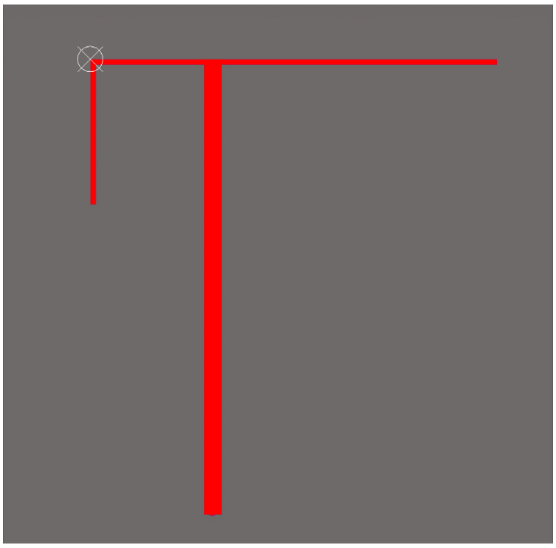


Fig: Antenna

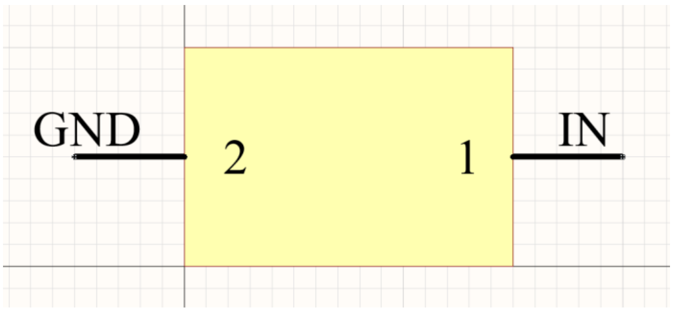


Fig: Schematic Library

We used the Inverted-F Antenna Design Walkthrough video series published by Altium Academy on YouTube and their guide on their website as reference for our designs.

10.12 Conclusion

The antenna design for the RFID project was a challenging yet rewarding task that provided invaluable insights into RF design and practical antenna engineering. The successful development and integration of the custom patch antenna have significantly enhanced the RFID reader's performance, demonstrating the importance of meticulous design and thorough testing in achieving optimal results.

11 System Integration

Our system comprises of three main components.

1. RFID Reader
2. Antenna
3. PC based GUI (Graphical User Interface)

11.1 Firmware Programming

The antenna design for the RFID project was a challenging yet rewarding task that provided invaluable insights into RF design and practical antenna engineering. The successful development and integration of the custom patch antenna have significantly enhanced the RFID reader's performance, demonstrating the importance of meticulous design and thorough testing in achieving optimal results.

While the RFID Reader has the microcontroller STM32L4 and the ST25RU3993 RFID reader IC, the project did not require us to write the code for the microcontroller since STMicroelectronics provides

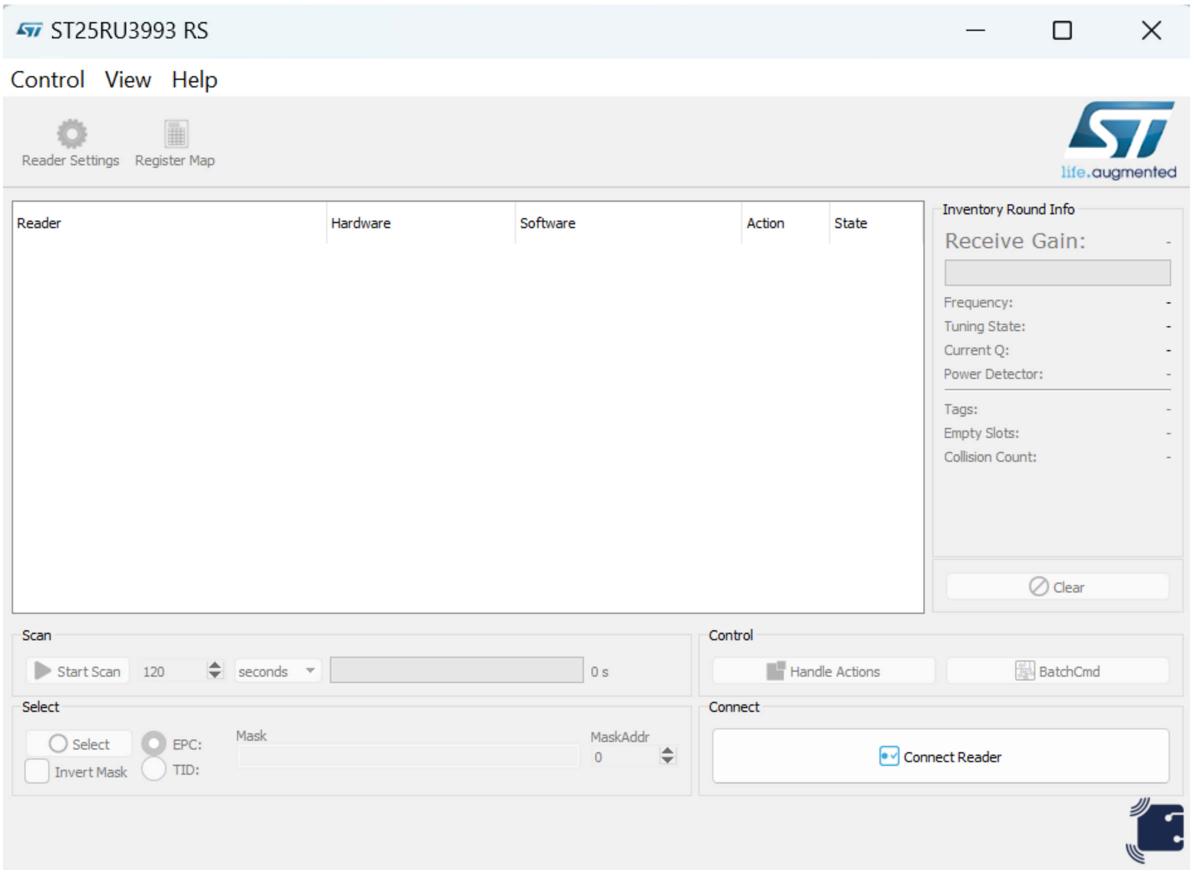


Fig: GUI of the PC Software STR25U3993 Reader Suite user a PC software to handle the firmware. STSW-ST25RU001 software comprises of the ST25RU3993 GUI (Graphical User Interface), which is a PC based application for Windows® platform. It allows connecting to the RFID Reader with the ST25RU3993 IC by an USB/UART bridge and controls the firmware running on the STM32L4 microcontroller. The ST25RU3993 GUI allows full control and low-level access to the ST25RU3993 RAIN® Reader device and is designed to demonstrate its main functionalities and features. The ST25RU3993 GUI controls scanning for RFID tags and displays relevant tag information such as EPC tag, number of found tags, tag's reads per second, tag RSSI and more. The ST25RU3993 GUI provides tag access functionality to read and write EPC, user memory and access and kill passwords as well.

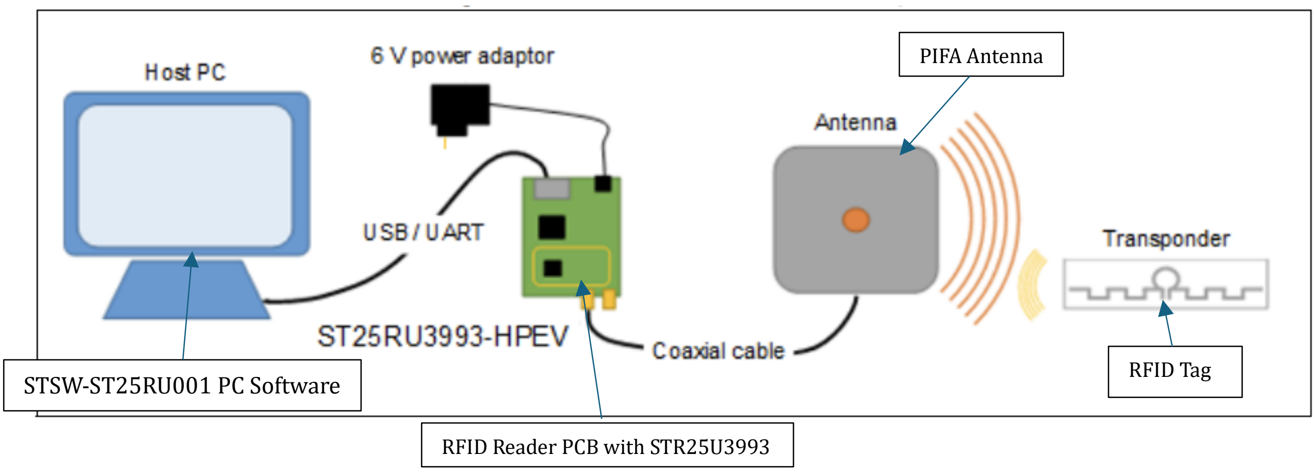
Since this software is available, we were not required to write any code for the microcontroller.

To use the PC software STR25U3993 Reader Suite, we need to have a working RFID Reader, which we do not have yet, due to the inability to solder the PCB at the moment. Below is the software without a RFID Reader being connected.

The RFID Reader board is controlled by a graphical user interface (GUI) running on a host PC. The corresponding interface is a USB/UART bridge (requires driver installation). The GUI can be found on dedicated pages on www.st.com. The board supports tuning the radio frequency from 840 to 960 MHz and provides two SMB (male) antenna connectors that can be controlled via the GUI. To enable scanning for RAIN RFID transponders, connect a suitable 50 Ω UHF antenna for the targeted frequency range.

The specific software used for this project is STSW-ST25RU001 as mentioned above. It is easy to be integrated with the rest of the components in the project since the RFID Reader IC and the microcontroller are both sourced rom STMicroelectronics as well. A demonstration video and further details such as features, and compatibility can be found in their website https://www.st.com/en/embedded-software/stsw-st25ru001.html.

The below diagram demonstrates the final look of the system once it is integrated with all the components: the PC software,



The interrogation of the system will be done once the PCB and antenna are soldered since a working PCB is required for the software to be used.

12 Soldering (Antenna and PCB)

This task has not yet been completed due to the inability to use the workshop since it is closed due to the non-academic staff strike. This will be completed, and the relevant documentation will be updated once it is done.

13 Testing (Antenna and PCB)

This task has not yet been completed due to the inability to use the workshop since it is closed due to the non-academic staff strike. This will be completed, and the relevant documentation will be updated once it is done.

14 Assembly

This task has not yet been completed due to the inability to use the workshop since it is closed due to the non-academic staff strike. This will be completed, and the relevant documentation will be updated once it is done.

15 Future Developments & Acknowledgements

15.1 Future Developments

In advancing handheld RFID reader circuits for warehouse management systems, delving into RF (Radio Frequency) theory research stands as a vital component. Understanding RF theory and exploring its applications could lead to breakthroughs in optimizing RFID reader performance, enhancing data capture capabilities, and improving overall system reliability.

One crucial aspect of future development involves a deeper exploration of RF propagation phenomena and electromagnetic wave behaviour. By gaining insights into RF theory, researchers can better understand the factors influencing signal propagation, attenuation, and interference in warehouse environments. This understanding can inform the design of RFID reader systems capable of mitigating the effects of multipath propagation, RF reflections, and environmental obstacles, thereby improving tag detection accuracy and system robustness.

Furthermore, investigating RF modulation techniques and signal processing algorithms holds promise for enhancing the efficiency and reliability of RFID communication. By leveraging advancements in RF modulation theory, researchers can develop novel modulation schemes optimized for warehouse applications, such as dynamic modulation schemes that adapt to changing environmental conditions or interference levels. Additionally, exploring advanced signal processing algorithms, such as digital filtering and error correction techniques, can help improve the accuracy of RFID tag detection and data decoding, even in challenging RF environments.

Moreover, studying RF interference mitigation strategies and spectrum management techniques is crucial for ensuring the reliable operation of RFID reader circuits in warehouse environments with potentially crowded RF spectrum. By researching RF interference suppression techniques, such as frequency hopping, spread spectrum modulation, or interference cancellation algorithms, researchers can enhance the resilience of RFID reader systems to external RF noise sources and co-channel interference, thereby improving overall system performance and reliability.

By integrating RF theory research into future developments of handheld RFID reader circuits, researchers can unlock new opportunities for innovation and optimization in warehouse management systems. Through interdisciplinary collaboration and a comprehensive understanding of RF principles, researchers can drive advancements that enhance the efficiency, accuracy, and scalability of RFID-based inventory tracking and management solutions in warehouse environments

15.2 Acknowledgement

We would like to sincerely thank and appreciate everyone who has contributed significantly to the creation of this exceptional product. This design document would not have been successfully realized without the combined efforts and support given from everyone.

First, we would like to express our sincere gratitude to our lecturer for his constant encouragement and support during this project. His dedication to innovation and strategic leadership have been crucial in helping to shape the idea and propel us toward success.

We also want to extend our heartfelt thanks to the group members from the main team involved in this project. Their unwavering support, continuous encouragement, rigorous testing, and meticulous attention to detail ensured that our product met the highest standards of dependability and performance.

Additionally, we are grateful to all the individuals who provided technical assistance and shared their expertise, which was instrumental in overcoming various challenges throughout the development process. The invaluable insights and guidance have greatly contributed to the successful completion of this project.

16 Datasheets

1. STM32 Microcontroller https://www.st.com/content/ccc/resource/technical/document/datasheet/c5/ed/2f/60/aa/79/42/0b/DM00108832.pdf/files/DM00108832.pdf/jcr:content/translations/en.DM00108832.pdf
2. ST25RU3993 IC https://www.st.com/en/nfc/st25ru3993.html.
3. NXP RFID https://www.nxp.com/part/SL3S1206FUD2.
4. RF IC Digitally Tunable Capacitor https://www.psemi.com/pdf/datasheets/pe64906ds.pdf.
5. 50V Ceramic Capacitor https://search.murata.co.jp/Ceramy/image/img/A01X/G101/ENG/GRM1555C1H3R6BA01-01.pdf.
6. 0.05pF 50V Ceramic Capacitor https://www.digikey.com/en/products/detail/murata-electronics/GRM1555C1H1R2WA01D/3693935

17 Datasheets

1. Inverted-F Antenna Design For a PCB https://resources.altium.com/p/inverted-f-antenna-design-pcb.
2. Antenna Theory https://www.antenna-theory.com/antennas/patches/pifa.php.
3. Microstrip Patch Antenna Calculator for RF Designers https://resources.altium.com/p/microstrip-patch-antenna-calculator-rf-designers.
4. User Manual https://www.st.com/resource/en/user_manual/dm00717148-highpower-rfid-reader-system-based-on-st25ru3993-stmicroelectronics.pdf
5. RFID Handbook: Fundamentals and Applications, Book by K. Finkenzeller https://repo.zenk-security.com/Magazine%20E-book/RFID_handbook.pdf.
6. RFID Toys, Book by Amal Graafstra https://books.google.lk/books?id=Irx2SjuF0gMC&printsec=copyright&redir_esc=y#v=onepage&q&f=false.

Appendix

Daily Log Entries

- **29 January – 4 February**

  During this week we had to select a suitable project and submit a proposal under the Electronic Design realization module. We did some research on suitable industrial level projects that can be done while adhering to the module outline and expectations. Upon researching on such projects, we identified the need for low-cost RFID Readers for warehouses in Sri Lanka since it is very useful in export and logistics. Hence, we proposed to design a RFID(Radio Frequency Identification Device) Reader for this purpose. After submitting our initial proposal, it was approved.

  As this area of electronics was new to us, we had to do some preliminary research on RFID principals and how it works. Furthermore, we had to learn how RFID is used for our application. We got a basic idea of how RFID works.

  Below are some references we used to understand and get an overall idea about RFID applications.
  - https://www.fda.gov/radiation-emitting-products/electromagnetic-compatibility-emc/radio-frequency-identification-rfid#:~:text=Radio%20Frequency%20Identification%20(RFID)%20refers,back%20from%20the%20RFID%20tag.
  - https://www.ar-racking.com/en/blog/rfid-technology-applied-in-a-warehouse-and-logistics/
  - https://www.google.com/search?q=rfid+readers&oq=rfid+readers&gs_lcrp=EgZjaHJvbWUqBggAEEUYOzIGCAAQRRg7MgYIARBFGDwyBggCEC4YQNIBCDM5NjBqMGoxqAIAsAIA&sourceid=chrome&ie=UTF-8

- **5 February – 11 February**

  As we got a basic understanding of the functionality of RFID. Now we had to get into the specifics of how this works for our application. Upon, research we understood that RFID applications are used in different frequency ranges based on its applications.
  - https://www.idtechex.com/de/research-article/rfid-frequency-bands/40

  We had to outline the requirements and constraints of our project. For our purpose of building a RFID Reader for a warehouse we understood that we need to choose a UHF RFID IC for our project based on the requirements of the project which was that we need to design this in such a way that RFID Tags up to a distance of 2 m can be detected.

- **12 February – 18 February**

  We researched on different stakeholder groups that will be involved with our project and each stakeholder's needs. Furthermore, we had to observe them and understand the interests of each stakeholder.

  This was the first we delved into the specifics of our project. We started to look for suitable ICs for our project and other references and guides such as research papers and user manuals. Upon researching these we identified a few major companies that design ICs for this purpose, namely Impinj, Zebra technologies, NXP and ST Electronics. Upon further investigation we released that obtaining an IC for major companies was hard and we decided to use the ST25RU3993U IC as we found High-power RFID reader system based on ST25RU3993 which was perfect for our purpose.

  We abstracted the key features for our project: strengths and weaknesses.

- **19 February – 25 February**

Since we had decided to use UHF for our project and had found the necessary manual to kickstart our project, we wrote down the main tasks that were ahead of us. They were,

- PCB Designing
- Enclosure Designing
- Antenna Designing

As antenna designing was a new field to us, our lecturer Prof. Kapila Jayasinghe, connected us with a pioneer in the field of RF: Prof. Aruna Gunawardena from the University of Peradeniya. During this week we spoke with him and understood how we should proceed with the antenna design. For this we were advised to first learn the basics of Antenna theory, and then attempt to design a simple microstrip patch antenna. We were given some websites to refer to. Furthermore, we were given a few software that is used for the purpose of designing and simulating antennas. Since these should be purchased, we had to research on how to get a licence for a low cost.

Since the PCB was a high frequency PCB design, we had to learn some new theory and do some research on this topic as well.

- **26 February – 3 March**

Upon research on Antenna Design software, we found that Ansys HFSS had a student package with limited features which was free. Despite the limitations it was suitable for our purpose. Therefore, we decided to choose Ansys HFSS as our software. We used this week to learn the basics of Microstrip antennas and the basics of HFSS. For this we used the following websites,

- https://athena.ecs.csus.edu/~milica/EEE212/HAND/HFSSintro.pdf
- https://www.antenna-theory.com/

We started reading the design guide which we decided to refer to after our lecturer recommended it as well. While the User guided included all the schematics and other necessary details to design the PCB, we came across a few questions such as,

- What are the parameters with red symbols?
- How to control impedance?
- What is the metal box on the PCB? (Which we later learnt that it was a RF Shield)
- Why cannot we get the impedance we require in microstrip lines using $R = {}^{\rho l}/_{A}$.

These were somethings we had to spend a lot of time on to understand.

- **4 March – 10 March**

We successfully designed our first Microstrip antenna using HFSS. While having the progress meeting with our lecturer and Prof. Gunawardena we learnt that in a successfully designed antenna the S parameter should be below -10dB and the dip should be at the centre frequency. These were things we did not have in our design. We were advised to design the antenna to a centre frequency of 915MHz.

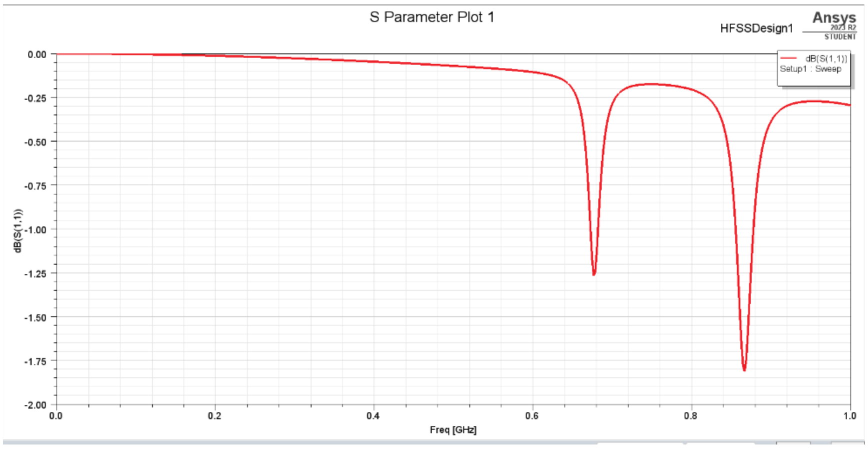


Fig: S parameter plot of our first antenna design

We were still learning and finding the answers to the questions we had regarding the PCB while referring to some research papers on the internet and asking our lecturer.

- **1 April – 7 April**

This week we were tasked with a very important aspect of our project: coming up with conceptual designs, we worked on this task, where we understood how to properly design an enclosure for a PCB and to compare important aspects of each design to ultimately choose one design as our final design.

We found most of the answers for the questions we had regarding the PCB. Hence, we started to check the availability of the components we need for our project. While the User guide recommended DigiKey as the supplier for the components we need, upon checking the availability of the components we found that some components were obsolete while some other components were not available in Digikey. Therefore, we found some replacement components for the obsolete ones and found other suppliers who have the unavailable components.

The next antenna design showed progress as it was commended in the progress review meeting, we had with Prof. Gunawardena. While we designed to a centre frequency of 915MHz, the S parameter and gain were low. We were advised to try to design a PIFA Antenna as well.

- **8 April – 21 April (Mid Break)**

We utilised the mid break to order the components and start drawing the schematic design. We successfully did both of these and started designing the PCB. While drawing the 9 schematic diagrams were tedious, it was rewarding. While designing the PCB we encountered some more questions such as,

- How to use via shielding properly?
- How can we reduce the cost of PCB fabrication given the cost to fabricate a 6-layer PCB?
- How to make test points on the PCB?
- How to impedance control using differential pairs?

After meeting our lecturer Prof. Jayasinghe, we got to know that we could use a different layer stack up for our PCB and we were guided on what to look for when researching on this. We found an answer to this by using an impedance-controlled layer stack up provided by our PCB fabricator JLCPCB. This reduced the cost significantly.

In the meantime, while learning how to design PIFA antennas we came across a toolkit that comes with HFSS which allows the user to synthesize an antenna after giving a few parameters such as the centre frequency and substrate hight. Using this tool we successfully designed a PIFA Antenna to our requirements. In the progress meeting with Prof. Gunawardena, we commended us on the success but expressed concern over the size of the antenna. We were advised to try to reduce it since we were planning to get the antenna fabricated for the laboratory in the University of Peradeniya and the size might make it unable to do so.

- **22 April – 28 April**

We received the components that we ordered from Digikey and the other suppliers. With the guidance of our lecturer Prof. Jayasinghe and a few knowledgeable seniors with experience in high-frequency PCB design we successfully placed the components and routed the PCB and sent it for fabrication to JCL PCB.

We designed an enclosure for the RFID Reader as well.

After a lot of trial and error we finally created a PIFA antenna of a smaller size and better s parameter value. But unfortunately, we came across a problem since the student version of HFSS doesn't allow the user to export the simulation file as a DXF file which is required to get the Gerber file. We were advised to send it to the technician in Peradeniya got get it converted as they have the Ansys HFSS licenced version.

- **29 April – 5 May**

We received the components along with the fabricated PCB. Due to the non-academic strike and the close down of universities we were unable to solder the PCB and get the antenna fabricated since the workshops and labs are closed in both University of Moratuwa and University of Peradeniya.

- **5 May - Present**

We have all the needful to solder and test the PCB and antenna but are unable to commence since the strike is still ongoing.

Review Declaration

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