Design Lab Project
on

Intelligent Reflecting Surface

submitted by

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Chapter 1

1.1 Introduction

IRS stands for Intelligent Reflecting Surface which is also known as reconfigurable intelligent surface (RIS), is an advanced hardware technology designed to control and manipulate electromagnetic waves in wireless communication environments. It consists of a two-dimensional array of many small, low-cost, passive reflecting elements—often called metasurfaces—that can individually adjust the phase (and sometimes amplitude) of incoming signals. By smartly tuning these elements, an IRS can manipulate and characterize the movement of electromagnetic waves by altering the electric and magnetic properties of the radio waves that are communicating nearby, enabling functions such as beam steering, interference mitigation, and coverage extension. the. Thus, it is widely recognized as an optimal solution to extend spectral efficiency and minimize the power requirements in 6G communications. Active IRS addresses the issue by introducing additional amplification and beam steering capabilities. This leads to a more complicated and expensive design from their operational perspective.

1.2 Motivation

Although The fifth-generation (5G) wireless network is still under deployment worldwide, both academia and industry have been enthusiastically looking into future beyond 5G such as the sixth-generation (6G) wireless network that targets at meeting more stringent requirements than 5G, such as ultra high data rate and energy efficiency, global coverage and connectivity, as well as extremely high reliability and low latency. Conventional wireless communication systems suffer from performance degradation in non-line-of-sight (NLOS) scenarios and highly dynamic environments. IRS has the potential to overcome these challenges by shaping the wireless channel proactively, thereby reducing reliance on complex active components like relays or MIMO antennas. By exploring an affordable and scalable IRS design using commercial passive components such as PIN diodes, this project aims to contribute toward the practical realization of low-cost reconfigurable metasurfaces suitable for future wireless networks like 6G.

1.3 Objective

The primary objective of this project is to design, fabricate and implement a functional prototype of a 4×4 Intelligent Reflecting Surface (IRS) to operate at 2.5 GHz, using PIN diodes for dynamic phase reconfiguration. The structure was implemented on an FR4 substrate ($\varepsilon r \approx 4.3$, thickness = 1.6 mm), offering a balance between cost and manufacturability.

Each unit cell was engineered to:

- Achieve a reflection coefficient magnitude greater than 0.9
- Provide a phase shift of approximately 180° between diode states (ON/OFF)

To enable the phase shift, Skyworks SMP1340-040LF PIN diodes were embedded in each element, allowing binary phase control via external DC biasing. The cell geometry was carefully optimized through electromagnetic simulations to ensure high reflectivity and minimal loss.

The biasing network was implemented using:

- Surface-mount components
- DC-blocking capacitors for RF isolation
- Optimized trace routing to avoid signal interference

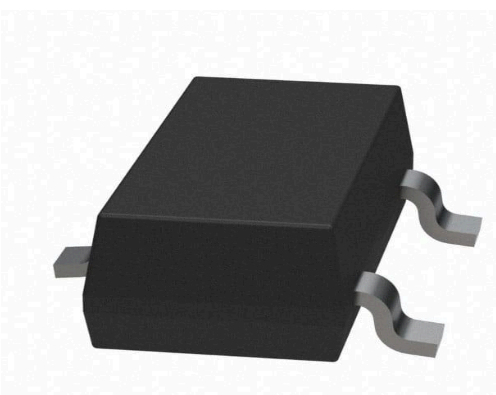
The complete 4×4 array was fabricated on a single-layer PCB. Post-fabrication, the IRS was evaluated using a vector network analyzer (VNA) under normal incidence conditions to characterize its reflection performance.

Chapter 2

2.1 Basic Components used

PIN diode:

The **Skyworks SMP1340-040LF** is a high-performance PIN diode optimized for RF switching and phase control in wireless systems, including reconfigurable intelligent surfaces (RIS). It comes in an ultra-miniature 0402 SOD-882 package, making it ideal for compact PCB layouts. This diode features low capacitance and fast switching capabilities, ensuring minimal signal loss and high isolation when properly biased.



Ni USRP:

The **NI USRP (Universal Software Radio Peripheral)** is a flexible software-defined radio platform developed by National Instruments. It enables real-time transmission and reception of RF signals across a wide frequency range and is commonly used for prototyping wireless communication systems in LabVIEW.

Inductors:

In RF circuits, inductors are commonly used to provide RF isolation for DC bias lines. This technique is known as using an **RF choke**. The inductor allows DC current to pass through to bias active components like PIN diodes or transistors, while blocking high-frequency RF signals due to its high impedance at RF frequencies. This prevents the RF signal from leaking into the DC bias circuitry, preserving signal integrity and preventing unwanted losses or distortions in the RF path.

Resistors:

Resistors are used in the setup to limit the flow of current in the circuit through the diode so the diode doesn't get damaged

FR4 substrate:

FR4 is a widely used dielectric substrate in RF and microwave circuit design, made from woven fiberglass cloth with an epoxy resin binder. It offers good mechanical strength and moderate electrical performance, making it suitable for prototyping and cost-effective designs. With a **thickness of 1.6 mm**, it provides structural stability and is compatible with standard PCB manufacturing

Copper patches:

In a **reflectarray** configuration, copper patches\unit cells act as passive or reconfigurable elements that reflect incident electromagnetic waves with a controlled phase shift. These patches are typically arranged in a periodic array on a dielectric substrate like FR4, and each patch can be individually designed or tuned to produce a specific phase response. This allows the reflectarray to shape or steer the reflected beam, combining the benefits of parabolic reflectors and phased arrays. The use of copper ensures low-loss reflection, while the patch dimensions and spacing determine the frequency response and beam direction.

2.2 Design

The design of whole setup of IRS is basically divided into 2 parts:

- Designing the layout and fabrication IRS on PCB.
- Communication using NiUSRP.

2.2.1 Layout

Unit cell:35mm*35mm.

nThickness:0.035mm.

slot width:0.2mm.

wavelength: 120mm(c/f).

Periodicity: 48mm

Element Spacing: The spacing between elements in the IRS is crucial because it impacts the performance of the surface. Typically, a spacing of half the wavelength (λ/2) is chosen for good performance in terms of beamforming and signal reflection. However, this distance can be adjusted depending on the design goals.

At 2.5 GHz, the wavelength is **120 mm**, so your periodicity of 48 mm becomes:

48/120=0.4λ

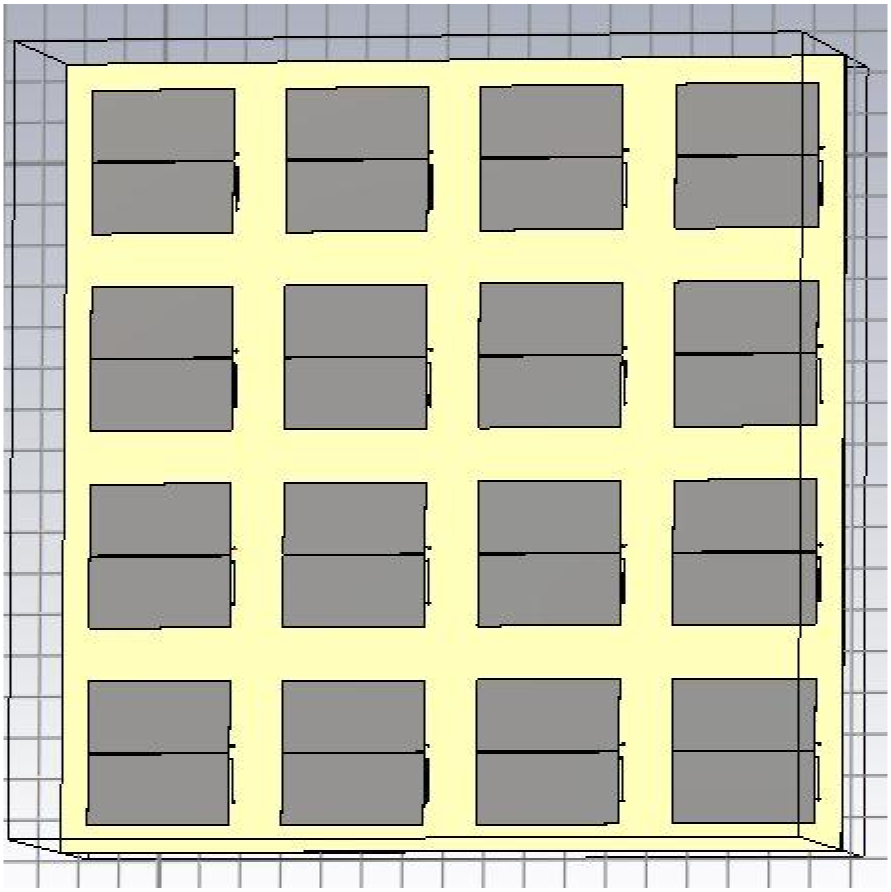
This is well within the safe range — below the **λ/2 threshold (60 mm)**, so it won't introduce **grating lobes**, and the surface can reflect incident waves effectively and with good angular resolution.

FR4 substrate: dimensions : 192mm*192mm

λ=f/c=2.5×1093×108=0.12m=120mm

Dielectric constant, k=4.4

Loss tangent = 0.02



2.2.2 RF Wireless Communication

The data in our system is transmitted wirelessly or through a direct RF cable connection between two laptops, each equipped with a USRP device. One laptop serves as the transmitter, and the other functions as the receiver. Both devices use LabVIEW to generate, modulate, transmit, receive, and demodulate digital signals in real time.

In our setup, we implemented a general digital communication system using LabVIEW and USRP devices. The system consists of two laptops—each connected to its own USRP device. We configured the system to allow communication over the air with antennas. This flexibility enabled us to experiment with both wireless and wired communication scenarios.

On the transmitting side, we generated a digital bitstream, which could either be a random binary sequence or data imported from a file. This bitstream represents the information we wanted to send. We then modulated this stream using Binary Phase Shift Keying (BPSK), though the system could be adapted for other modulation schemes like QPSK or QAM. After modulation, we mixed the signal with a carrier to shift it to the desired RF frequency(2.5GHz). LabVIEW’s graphical interface made it easy for us to configure parameters such as carrier frequency, sample rate, and transmission gain. The modulated signal was sent to the USRP, which transmitted it through the antenna or RF cable.

On the receiving end, the USRP captured the transmitted RF signal and down-converted it to a digital baseband signal, which was then processed using LabVIEW. We used a demodulation block to recover the original data. This process required synchronization and phase recovery to ensure that the transmitted bits were accurately decoded. To assist with synchronization, we included a known preamble in the transmitted data, which allowed the receiver to lock onto the signal and properly align the frames.

To verify the system's performance, we used LabVIEW's built-in visualization tools. These tools displayed the transmitted and received waveforms, as well as constellation diagrams. We also calculated the Bit Error Rate (BER) to evaluate the effectiveness of the communication under different channel conditions. This experiment provided us with valuable hands-on experience in digital communication systems, signal processing, and real-time software-defined radio platforms. It was a great opportunity to apply theoretical knowledge in a practical environment.

Chapter 3

3.1 Simulation Results

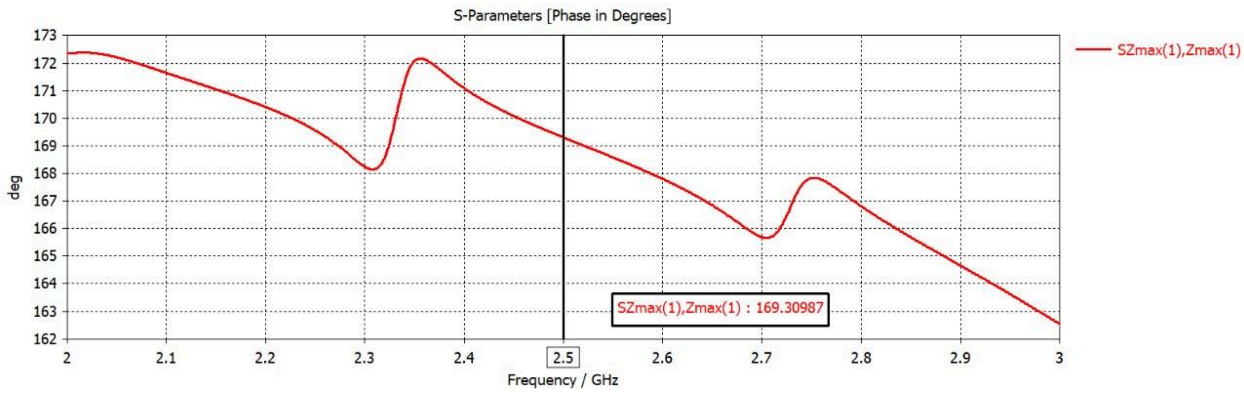
S-Parameter Simulation Results for PIN Diode States

The performance of the designed reflective surface is analyzed using S-parameter simulations in both the **ON** and **OFF** states of the PIN diode. The simulations span the frequency range from **2 GHz to 3 GHz** and are evaluated in terms of the phase and magnitude of the reflection coefficient S11S_{11}S11, both in linear and logarithmic (dB) scales. These results help assess the reflectivity and phase shifting behavior essential for reconfigurable intelligent surfaces.

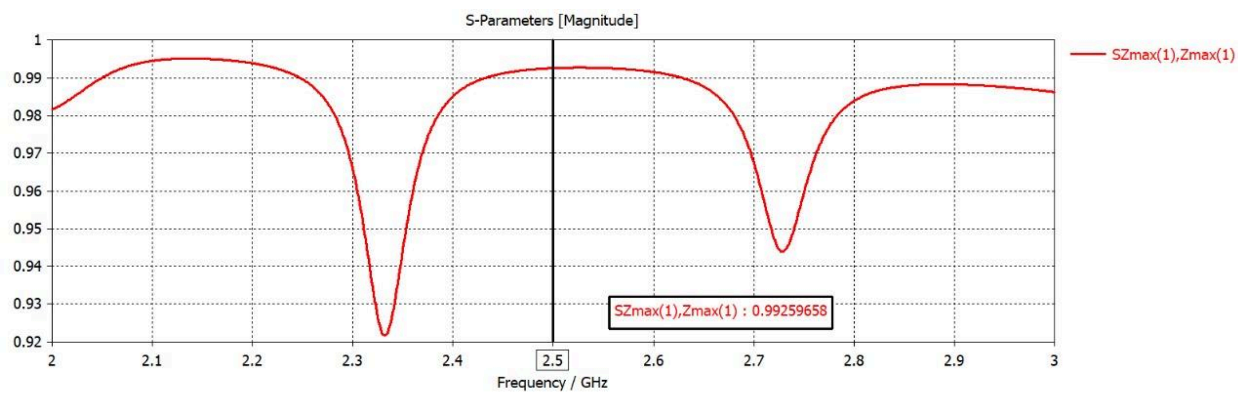
1. ON State of the PIN Diode

When the PIN diode is forward-biased (ON state), the structure is expected to provide a specific reflective behavior with minimal reflection loss and a distinct phase profile.

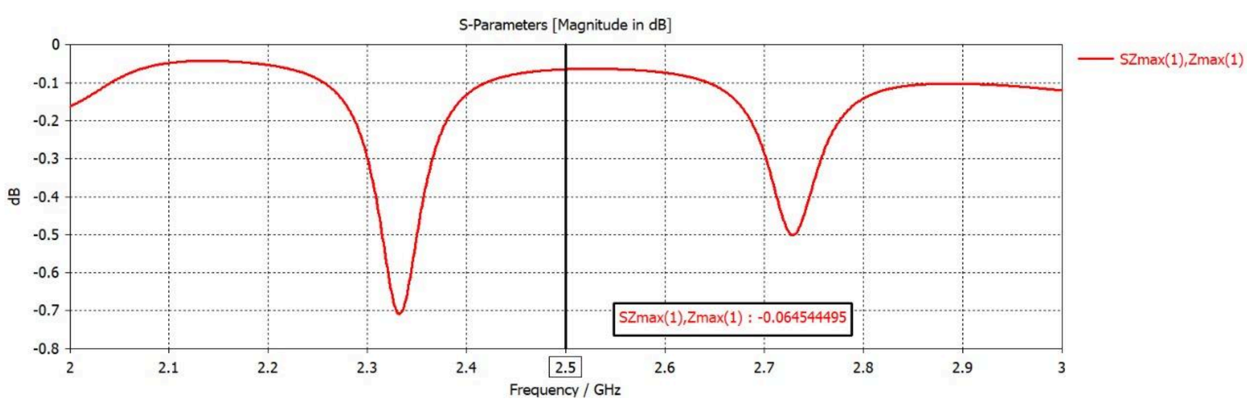
- **Phase Response :** The phase decreases smoothly from **~170° at 2 GHz** to **~145° at 3 GHz**, with slight fluctuations near 2.35 GHz and 2.7 GHz. At the operating frequency of **2.5 GHz**, the phase is **164.69°**, offering consistent reflective behavior across the band.



- **Magnitude (Linear) :** The magnitude of reflection remains above **0.98** throughout most of the frequency range. A minimum occurs around **2.33 GHz**, indicating a resonance. At **2.5 GHz**, the magnitude is **0.9926**, which shows **high reflectivity** and **low insertion loss**.



- **Magnitude (dB) :** The minimum reflection dip reaches about **–0.74 dB** at 2.33 GHz, with another slight dip near 2.7 GHz. At the target frequency of 2.5 GHz, the reflection coefficient is **–0.0645 dB**, confirming excellent performance



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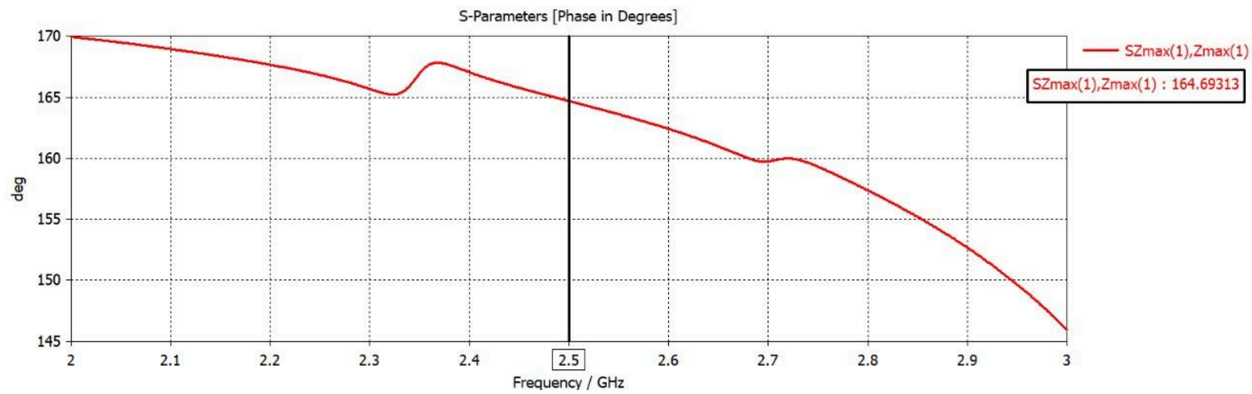
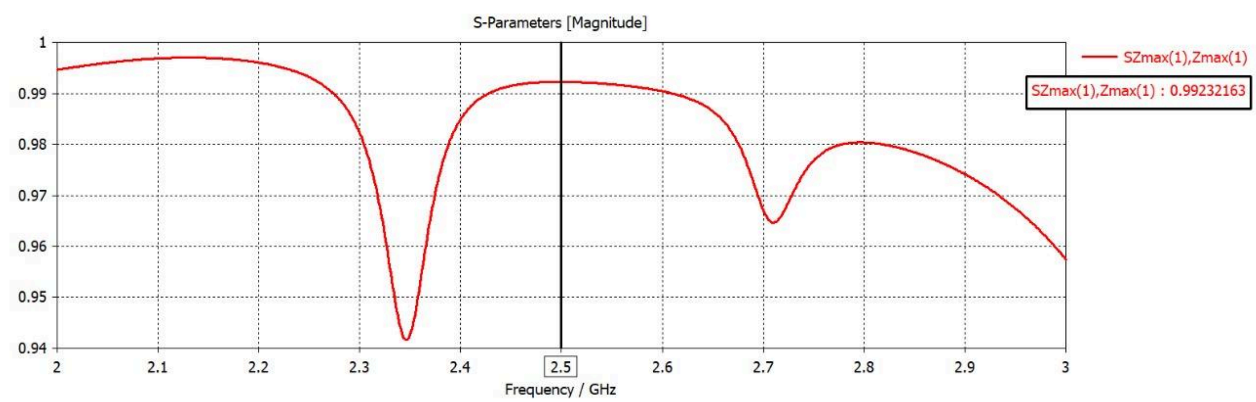
2. OFF State of the PIN Diode

When the PIN diode is reverse-biased (OFF state), the reflective behavior is expected to change, allowing for phase modulation and variable reflectivity—key aspects for dynamic beam control.

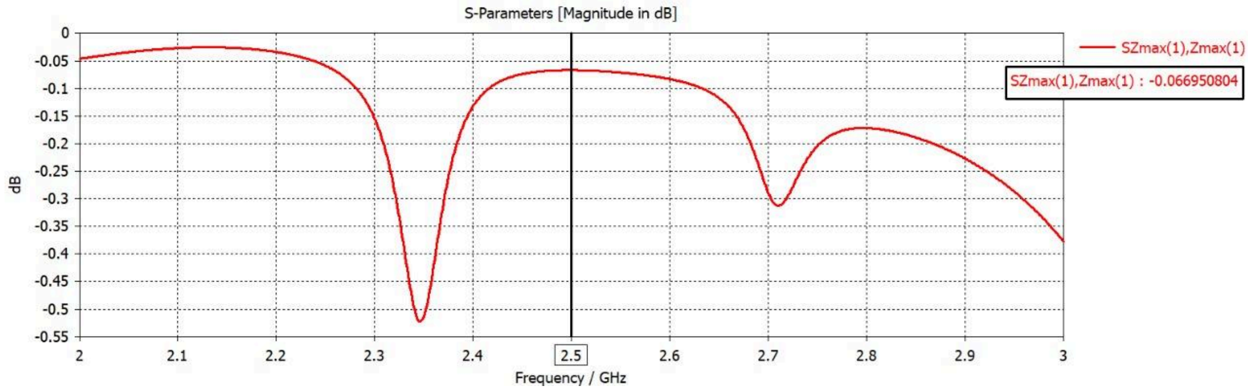
- **Phase Response :** The phase profile is nearly identical to the ON state, beginning at **~170°** and tapering to **~145°**, with minor deviations due to the diode's altered impedance. At 2.5 GHz, the phase remains **164.69°**, indicating minimal phase change between states.



- **Magnitude (Linear) :** The reflection coefficient remains high across the band, with a minimum around **2.33 GHz**. At 2.5 GHz, the magnitude is slightly reduced to **0.9923**, which is still **highly reflective**.



- **Magnitude (dB) :** Reflection dips down to about **–0.49 dB** at resonance. At **2.5 GHz**, the reflection is **–0.0669 dB**, confirming that the OFF state also provides efficient reflection but with subtle variation compared to the ON state.



The simulation results show that both ON and OFF states of the PIN diode maintain high reflectivity with minim

al losses across the desired band. The key difference lies in the minor changes in reflection magnitude and slight variations in phase, which are sufficient for practical reconfigurable surface applications such as beam steering or phase coding. The selected operating point at **2.5 GHz** demonstrates optimal performance in both states.

Chapter 4

4.1 Conclusion:

We designeda functional 4×4 Intelligent Reflecting Surface operating at 2.5 GHz using PIN diode-based reconfiguration. The system demonstrated high reflectivity and stable phase response, validating its potential for beam manipulation in wireless communication. We also integrated this IRS with a USRP-based communication setup, enabling real-time transmission and reception. The results confirm the feasibility of using low-cost, reconfigurable metasurfaces for improving wireless coverage and efficiency, laying a strong foundation for future developments in 6G communication technologies.

4.2 Future work:

In the future, we aim to expand our IRS prototype to larger array sizes, such as 8×8 or 16×16, to improve beamforming accuracy. We also plan to achieve full 360° phase control for enhanced signal manipulation. Integrating real-time control using microcontrollers or FPGAs will allow dynamic beam steering. Additionally, we intend to explore hybrid designs with active elements, implement machine learning-based optimization for channel estimation, and test the system in real-world environments to evaluate its practical performance. Lastly, we will extend the setup to support multi-user and MIMO scenarios for broader 6G applications.