Design of Smart Reconfigurable Surfaces for Wireless Networks

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DECLARATION

I hereby, declare that this manuscript, entitled “Design of Smart Reconfigurable Surfaces for Wireless Networks”, is the result of my own work except for quotations and citations which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

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Abstract

This thesis examines the development and implementation of reconfigurable intelligent surfaces (RIS) to improve the performance of wireless communication networks. Due to the rapid development of wireless communication technologies, the need for higher data transfer speeds, improved coverage and efficient use of spectrum is more urgent than ever. Traditional communication networks face difficulties in meeting these requirements due to dynamic changes in user density, signal interference and transmission conditions. RISs are becoming a promising solution to overcome these obstacles by allowing the dynamic manipulation of electromagnetic waves, thereby revolutionizing the design and operation of networks.

We are implementing new RIS architectures integrating active diode elements to enable real-time reconfiguration, thereby increasing adaptability and versatility in changing environments. The research includes a comprehensive study of existing technologies, the development of design methodologies for intelligent RIS and extensive simulation studies to assess their performance. Our results demonstrate the possibility of using 2-bit and 3-bit RIS matrices for dynamic phase manipulation of reflected signals, demonstrating significant improvements in network performance indicators such as signal coverage, bandwidth, and interference reduction.

This thesis not only contributes to the development of Smart RIS technology, but also opens new opportunities for research and development in the field of wireless communications, which is important for future technologies, including 5G and beyond. The work presented here highlights the importance of integrating advanced materials and electronic control mechanisms in the design of RIS, paving the way for more efficient and adaptable wireless networks.

Acknowledgements

I am profoundly grateful to Dr. Galymzhan Nauryzbayev and Dr. Almas Shintemirov for their exceptional guidance and mentorship during my studies. Their unwavering support and insightful direction have been instrumental in my successful completion of this Master’s program. I am particularly thankful for the extensive discussions we've had, particularly in the realms of communications and embedded systems.

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Last but not least, I extend my heartfelt appreciation to my friends and colleagues who have supported me along this challenging yet rewarding path. Their encouragement and camaraderie have made this journey memorable.

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List of Abbreviations

AVs/CVs	Autonomous vehicles/connected vehicles
eMBB	Enhanced mobile broadband
IOT	Internet-of-Things
ISM	Industrial, Scientific, and Medical
MEMS	Microelectromechanical systems
mMTC	Mass Machine Type Communication
NOMA	Non-orthogonal multiple access
PLC	Power line communications
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
SINR	Signal-to-interference & noise-ratio
SNR	Signal-to-noise ratio
SWIPT	Simultaneous wireless information and power transfer
URLLC	Ultra-reliable low latency communication
UAV	Unmanned aerial vehicle
5G	Fifth generation

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Chapter 1 - Introduction

1.1 General

In the rapidly developing wireless communication system, there has been a significant increase in demand for uninterrupted communications, higher data transfer speeds and efficient use of spectrum. The user densities of traditional wireless networks change dynamically and are also coupled with challenges presented by signal interference and changing transmission conditions, thus requiring smart and innovative solutions. "Smart reconfigurable surfaces", or "reconfigurable intelligent surfaces" can point the way forward. All these surfaces are formed by a large quantity of passive elements, which are generally called meta-atoms or unit cells [1]. Such elements present features of electronic control that let the altering of the phase, amplitude, and direction of the electromagnetic waves falling from them [2]. These surfaces can revolutionize to a very large extent the design and operational fabric of the network because of their intelligence to manipulate the wireless signals [3].

1.1.1 Emergence of RISs

The key to making RISs work is the ever-increasing demand for wireless communication systems that can adapt to the dynamic, most often uncertain, nature of the radio frequency (RF) environment. However, the user needs of faster and better connection mean that traditional network architectures are overstretched in tackling the multiple challenges of signal propagation. RISs, in their nature of reconfigurability, bring something promisingly new: a paradigm where the environment becomes an active participant in signal optimization. They offer flexibility in never-before signal propagation management, with the capability of dynamically controlling electromagnetic waves at the surface [2].

1.1.2 Core Principles of RISs

The main point of RIS technology lies the complicated control over electromagnetic waves through passive elements. This kind of passive elements is usually made of materials like metamaterials, or they use active elements like varactor diodes that get dynamically controlled to change the characteristics of the impinging RF waves [4]. On the very basic principles, RIS allows for control over phase, amplitude, and polarization of the incident waves [5], to provide customization in the control of signal propagation for tailor-made purposes like beamforming, suppression of interference, and improvement of coverage in difficult environments.

1.1.3 Inspirations from Varied Disciplines

The development of RISs brings various disciplines that inspire perspectives in this changing technology. Metamaterials, a new whole field born out of an effort to make materials having electromagnetic properties not naturally occurring, providing the foundational base for unconventional signal manipulation [5]. Antenna theory and beam-shaping techniques provide essential details on how electromagnetic radiation is able to be captured and controlled for specific uses [6]. Such inclusion of ideas into the RIS design helps in the multiplication of its' potential for wireless control.

1.1.4 Advantages and Challenges

The use of RIS in wireless network infrastructures has its fair share of boons. These include increasing the strength of the signal, decreasing interference, allowing good coverage even in obstructive environments, and allowing for the establishment of dynamic links of communication that change with the prevailing conditions. It adds another level of flexibility to the environment, so that network managers have a higher level of control over how the performance of the network could be improved by controlling different elements with the RIS-enabled surfaces [7]. However, the embedding of RISs in wireless networks brings its share of difficulties [8]. The challenges' needs must be surfaced with proficient knowledge in electromagnetic theory, signal processing, and various optimization techniques. Further, deployment of such surfaces also requires addressing issues related to power consumption, cost-effectiveness, and integration with the existing network infrastructure [8].

1.1.5 Significance of RISs in Modern Communication

With wireless communication and permeating smart cities and other forms of Internet of Things (IoT), revolutionary solutions like RISs have a great future ahead to define the future of wireless networks. Research in this domain tries to find answers to some of the most fundamental questions about design methodologies, optimization algorithms, and practical implementation strategies that would unlock the transformative benefits from these intelligent surfaces.

1.2 Aims and Objectives

The main goal of this thesis is to delve into the creation and application of Smart RIS to boost the functionality and effectiveness of wireless communication networks. Traditional RIS designs typically rely on static elements, such as printed patterns, to manipulate electromagnetic waves. Yet, this method is somewhat restrictive in its flexibility and adaptability when faced with the ever-changing conditions of wireless networks. As such, this study aims to look into innovative RIS designs that incorporate active elements, like diodes, allowing for the surface properties to be adjusted in real-time.

The detailed goals of this research are outlined below:

- Explore the core concepts and current advancements in RISs and their role in wireless communications. This examination aims to offer a thorough overview of cutting-edge progress and pinpoint unaddressed areas in existing studies.

- Develop design methodologies for Smart RIS incorporating active diode elements, such as RLC diodes and varactor diodes. This includes examining the electromagnetic attributes, choosing the right materials, and integrating circuits to meet the demands of wireless networks.
- Design and simulate a 2-bit RIS array utilizing RLC diodes for dynamic phase manipulation of reflected signals. Here, the goal is to showcase the benefits and practicality of embedding active components to improve the flexibility and efficiency of RIS in wireless environments.
- Extend the design to a more complex 3-bit RIS configuration, employing varactor diodes for continuous phase tuning across a wider range of frequencies. This phase is dedicated to further confirming the benefits of adding active elements to RIS designs and to assess their influence on network performance indicators.
- Evaluate the performance of the proposed Smart RIS designs through comprehensive simulation studies and experimental validation. It entails evaluating crucial factors like side lobe gain level, main lobe gain magnitude and direction, angular width, overall network performance in different conditions and setup configurations.

By meeting these objectives, the research intends to further the development of Smart RIS technology and shed light on its potential to transform wireless communication networks. The outcomes of this study are expected to have implications for future research directions, standardization efforts, and practical implementations in diverse application domains, including fifth generation (5G) and beyond-5G wireless networks, Internet-of-Things (IoT) systems, and beyond.

1.3 Literature Review

The swift progress in wireless communication networks has spurred the quest for cutting-edge technologies to fulfill the increasing demand for seamless and top-notch connectivity. Among these technologies, RISs have become a transformative solution capable of revolutionizing wireless communications in the 5G era and beyond [3]. RIS are an advanced technology ready to transform wireless communication networks. At its core, RIS involves the use of specially designed surfaces containing a variety of reflective elements strategically placed in a communication environment. In comparison with conventional passive reflectors, these intelligent surfaces are endowed with the ability to dynamically manipulate electromagnetic waves, providing unprecedented control over the propagation and distribution of the signal [3].

The idea of smart surfaces is rooted in the early research within electromagnetism and antenna theory, which investigated how reflective surfaces could enhance wireless communications. Traditional approaches have focused on stationary reflectors, which, although effective in extending the coverage area and reducing interference to some extent, did not have the adaptability necessary to solve problems arising in dynamic communication environments [4]. This limitation prompted a paradigm shift towards the development of reconfigurable surfaces capable of actively adjusting their properties in response to changing network conditions.

Over the years, advances in materials science, signal processing, and optimization techniques have contributed to the evolution of RIS from passive reflectors to intelligent adaptive surfaces. By integrating active elements such as diodes and varactors into the surface structure, the researchers have opened many possibilities for detailed control of signal manipulation [2, 9]. These active components provide dynamic modulation of phase, amplitude, and polarization characteristics, facilitating tasks such as beam shaping, zero control, and interference suppression with exceptional precision [9].

Against the background of the growing IoT and the upcoming introduction of 5G systems, the role in shaping the future of wireless communications cannot be overestimated. The potential of RIS to boost signal strength, broaden network reach, and enhance efficiency in using the spectrum is set to transform various domains, from indoor wireless setups to cellular networks and more [3]. Therefore, grasping the essential theories, design strategies, and practical impacts of RIS tech is crucial for both scholars and industry professionals aiming to maximize its benefits for achieving widespread and reliable connectivity.

The journey of RIS began with the foundational studies in wireless communication and electromagnetism. The use of passive reflectors to enhance signal travel isn't new, but the late 20th century brought about a significant shift with the introduction of surfaces that could be actively controlled [10]. Early 21st-century research [10] brought the concept of metamaterials into the limelight - these are artificially engineered structures that possess electromagnetic characteristics not found in natural substances, paving the way for the creation of smart surfaces that can actively steer electromagnetic waves. By the 2010s, the focus shifted towards leveraging reconfigurable components like electronically adjustable materials and microelectromechanical systems (MEMS) for the real-time tuning of surface attributes [10], signaling a leap forward in crafting intelligent surfaces that adapt instantly to alterations in their surroundings.

The article [17] designs print based RIS with the two-phase shift states, which are generated by controlling the ON/OFF states of the diode. This research [17] presents the development and thorough assessment of a 160-element RIS, fine-tuned for the 5.8 GHz frequency range, as illustrated in Figure 1.1 [17]. It is hereby noted that the measurements at this point were carried out in an anechoic chamber to motivate the real-world tests that will follow.

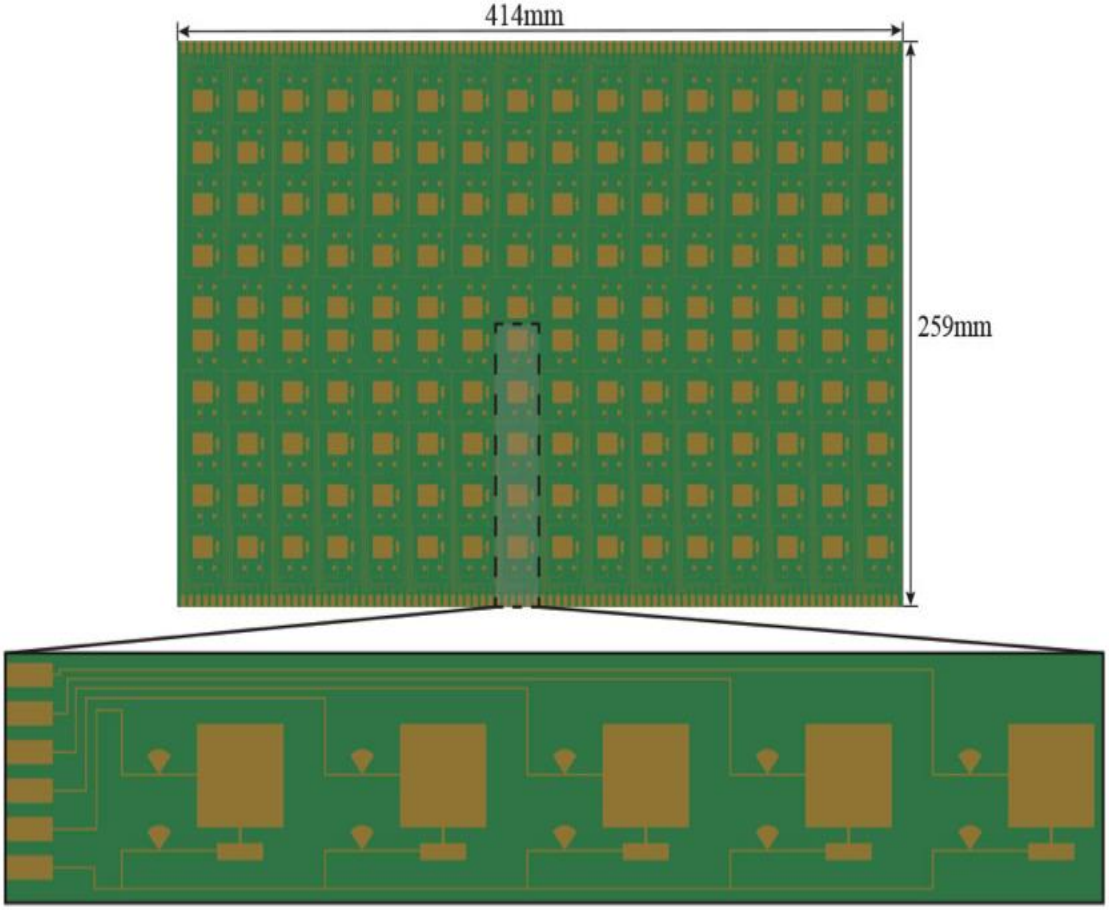


Figure 1.1: 160 RISs (16 x 10) array [17]

A pivotal finding of the study [17] is the substantial improvement in signal-to-noise ratio (SNR) facilitated by the RIS. More specifically, it was established that the prototype of RIS provides great support in a way that there is a 15–20 dB gain in SNR when used with directional antennas at both transmitter and receiver ends over ±60° on the beamforming angle. This enhancement is not just limited to SNR gains, the prototype significantly augmented coverage as well. In the experiment with a far-field setting, to imitate real settings where a blockage, which may include buildings or other structures, obstructs the signal path between the mobile user grid and its serving base station, RIS enhances an average SNR of up to 6 dB at points that may reach 8 dB, hence effectively providing coverage at over 35 m². The study [17] brings out the scalability of RIS designs; a bigger 1,600-element RIS could theoretically bring even more significant gains, which such deployments could realize a 26dB SNR improvement.

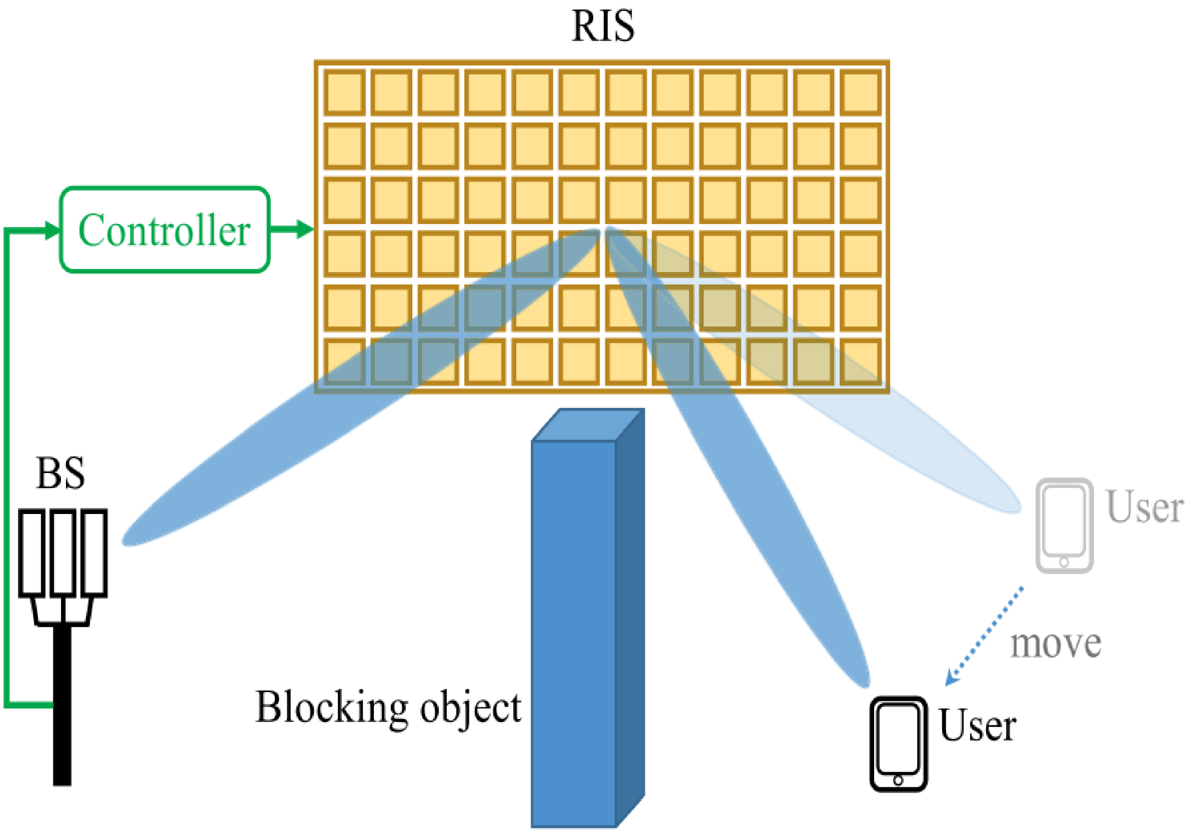


Figure 1.2: RIS-assisted wireless communication [27]

The articles [15, 27, 28] also discuss the integration of RIS with printing technologies, demonstrating their potential to revolutionize various applications. These include improvements to wireless IoT networks, communication systems with support for unmanned aerial vehicles (UAVs), and improved millimeter wave communications by eliminating blocking problems. In addition, RIS is used in multi-antenna systems to improve network performance. The practical implementation of these systems faces problems such as the need for controlled reflection, which can be solved using mechanical control, functional materials and electronic devices.

One of the notable milestones in the development of RIS, when researchers [11] demonstrated the concept of "meta-surfaces". They are ultrathin planar structures consisting of subwavelength elements capable of controlling the phase, amplitude and polarization of electromagnetic waves. This breakthrough has opened up new opportunities for the development of compact and efficient RIS solutions for wireless communication systems. Since then, there has been a surge of interest and research activity in the field of RIS, with numerous studies focusing on optimization algorithms, experimental demonstrations, and theoretical analysis. Recent advances have led to the integration of active components such as diodes and varactors to enhance the adaptability and performance of RIS in dynamic wireless environments [12].

RIS represent a paradigm shift in wireless communication systems, offering a new approach to electromagnetic wave control to improve signal propagation and network performance. At their core, RIS are flat surfaces consisting of a variety of passive or active elements capable of dynamically regulating the electromagnetic properties of the environment [6]. In comparison with traditional reflective surfaces, RIS have the ability to actively control the phase, amplitude and polarization of incident waves, allowing fine manipulation of signal characteristics. RIS have attracted significant attention due to their ability to increase the bandwidth and coverage of wireless networks by intelligently reconfiguring the wireless information distribution environment [13]. These surfaces offer a promising path to meet the diverse requirements of modern communication systems, including enhanced mobile broadband (eMBB), ultra-reliable low latency communication (URLLC) and mass machine type communication (mMTC) [13]. The integration of RISs with advanced technologies such as non-orthogonal multiple access (NOMA), ground-based UAV networks, power line communications (PLC), simultaneous wireless information and power transform (SWIPT) and autonomous vehicles/connected vehicles (AVs/CVs) opens wide possibilities for optimization of wireless networks and introduction of new applications [13].

The central element of the RIS conceptual framework is the principle of wavefront manipulation. By strategically adjusting the phase shift introduced by individual elements into the RIS matrix, electromagnetic waves can be directed and focused in the direction of desired recipients or users. This feature is especially valuable in scenarios where traditional beamforming techniques face limitations due to obstacles or multipath propagation [14]. Moreover, RIS can use the principles of constructive interference to increase signal strength and coverage in certain areas of interest, thereby improving overall network performance indicators such as signal-to-interference & noise-ratio (SINR) and spectral efficiency [14].

The key to understanding how RIS works is the concept of reconfigurability. In comparison with static reflective surfaces, RIS can adapt their behavior in real time in response to changes in the wireless environment or user requirements. This adaptability is facilitated by the integration of active components such as diodes and varactors, which allow dynamic control of the electromagnetic properties of the surface [12]. For example, by adjusting the bias voltage of varactor diodes, it is possible to adjust the capacitance and, consequently, the phase shift of individual elements, which allows optimizing the directivity of the signal and the beam formation scheme on-the-fly [12].

Recent advances in RIS research have made it possible to use concepts from areas such as metamaterials and intelligent materials to further enhance the capabilities of these surfaces [10]. Metasurfaces, for instance, provide unprecedented control over the electromagnetic response of materials at subwavelength levels, opening up new possibilities for designing compact and efficient RIS with individual electromagnetic properties [10]. In addition, the integration of machine learning algorithms for intelligent RIS management opens up prospects for autonomous adaptation and optimization in dynamic wireless environments, paving the way for self-adjusting and self-optimizing networks [8].

Existing approaches to RIS design and optimization cover both traditional passive reflector surfaces and more advanced intelligent RIS configurations combining active components such as diodes and varactors [9]. Passive reflective surfaces, which are a fundamental approach in this field, are characterized by their static nature, providing fixed reflective properties determined during the production process. While passive surfaces have demonstrated effectiveness in extending the signal coverage and minimizing interference, their lack of adaptability limits their use in dynamic wireless environments [12].

On the contrary, new configurations of intelligent RIS represent a significant evolution in this field, since they use active components to achieve dynamic control of reflection and signal transmission properties. One of the important active elements used in intelligent RIS designs is a diode, which provides the ability to adjust and adapt to the surface [2]. For example, RIS arrays containing diodes, such as RLC diodes, allow precise control of phase shifts and signal directivity [12]. The study [9] showed that in RIS, when using RLC diodes, an energy efficiency increase of up to 80% is achieved compared to passive reflectors, which emphasizes the effectiveness of active components in increasing productivity. In addition, varactor diodes are used in smart RIS configurations to ensure continuous adjustment of capacitance values, which allows detailed control of phase modulation and beam control [9]. The study [12] demonstrated the effectiveness of varactor-based RIS in dynamic channel media, which significantly increased spectral efficiency and expanded the coverage area. For instance, a 3-bit RIS array with varactor diodes demonstrated a 25% increase in coverage area compared to traditional passive reflectors in urban wireless environments [12].

Deploying RIS in wireless networks poses a number of serious challenges that need to be addressed in order to fully realize their potential. One of the key problems is dynamic adaptation to the environment, when the wireless channel experiences fluctuations due to the movement of transceivers, objects or changes in environmental conditions. For example, in urban environments, where the deployment of RIS is particularly promising, the dynamic nature of the environment creates problems for maintaining optimal signal reflection and propagation paths [8]. Studies have shown that even minor movements of objects near RIS can significantly change channel characteristics, which requires the use of rapid adaptation mechanisms to ensure continuous performance optimization. Using RIS to create intelligent radio communication systems creates both challenges and opportunities in wireless communication systems. In dynamic environments where the wireless channel is subject to frequent changes due to the movement of transceivers or objects, learning methods must adapt quickly during channel negotiation to maintain efficiency [8]. Moreover, optimizing the RIS configuration is a serious problem, especially in scenarios involving multiple users and RIS departments, where the complexity of optimization is compounded by the difficulty of obtaining accurate channel information [15].

However, among these challenges, there are attractive opportunities to improve system performance and simplify data processing. RIS has the potential to significantly improve the overall performance of the system by controlling the propagation of electromagnetic waves, thereby increasing the received power, affecting channel characteristics, providing spatial multiplexing and reducing interference [15]. In addition, RIS can simplify processing on the transmitting and receiving sides by transferring complexity to the optimization process of the RIS controller. In addition, the dynamic nature of the interaction between RIS and the environment represents an ideal scenario for the application of reinforcement learning methods, since sparse environmental sensors facilitate data collection for centralized controllers for adaptive optimization of RIS configurations [8]. By addressing these challenges and taking advantage of the opportunities that open up, RIS promises to revolutionize wireless communication systems by offering unprecedented flexibility and efficiency [15].

Another major problem is the difficulty of optimizing RIS configurations, especially in scenarios involving multiple users, multiple RIS modules, and dynamic channel conditions. The optimization task is becoming increasingly difficult due to the large number of variables involved, including the placement of RIS elements, the choice of phase shifts or impedance values, as well as the coordination of RIS blocks to achieve the desired goals of the system [16]. Research shows that it can be difficult for traditional optimization methods to find globally optimal solutions in a reasonable time, which underscores the need for innovative optimization algorithms and methodologies adapted to RIS-enabled networks [16].

In addition, accurate channel modeling and evaluation are important but challenging aspects of implementing RIS. The question of the possibility of obtaining accurate channel estimates and selecting suitable channel models for various RIS implementations remains open. Empirical studies have revealed discrepancies between theoretical channel models and measurements in the real world, emphasizing the need for reliable assessment methods that can accurately reflect the complexities of the wireless distribution environment [6]. In addition, the dynamic nature of the wireless channel creates additional difficulties, such as time-varying channel operating conditions and spatial variations, which further complicates the process of modeling and evaluating the channel [6].

In recent years, researchers have proposed various modern solutions to solve problems related to the design and optimization of RIS for wireless networks. One notable area of innovation is the development of new algorithms adapted to the configuration and optimization of RIS. For example, researchers have explored machine learning-based approaches such as deep learning and reinforcement learning to automatically learn and adapt RIS configurations in dynamic wireless environments [8]. These algorithms use large-scale datasets and advanced optimization techniques to improve the efficiency of RIS deployment [8, 16]. In the article [17], a prototype RIS was developed, consisting of 160 elements operating at a frequency of 5.8 GHz. RIS was designed, manufactured and measured in an anechoic chamber. The aim of the study was to evaluate improvements in beam shaping, trajectory loss and improved RIS coverage in realistic outdoor communication scenarios. The evaluation results showed that RIS achieved a significant increase in the signal-to-noise ratio (SNR) by 15-20 dB when both the transmitter and receiver used directional antennas [17]. This improvement in SNR demonstrates the potential of RIS in improving wireless performance. Moreover, the article [18] presents the concept of RIS as a programmatically controlled flat surface consisting of a variety of inexpensive passive reflective elements, with the ability to change the phase of the incident signal and create a favorable wireless environment between the transmitter and receiver. Moreover, researchers have proposed metaheuristic algorithms, such as genetic algorithms and particle swarm optimization, to explore the vast design space of RIS configurations and determine optimal solutions in a computationally efficient way [20]. To conclude, experimental methods play a crucial role in verifying the proposed solutions and evaluating their effectiveness in real conditions. The researchers conducted extensive field tests and simulations to evaluate the effectiveness of RIS in various wireless communication scenarios. These experiments often involve measuring signal strength, bandwidth, and bit error rates in different environments and under different network conditions.

Chapter 2 – Methodology of Research

This chapter describes the methodology adopted for designing, modeling, and prototyping of RIS adapted for wireless networks, with an emphasis on achieving improved reconfigurability and performance.

2.1 Designing 2-bit RIS

The initial stage of the methodology includes the design and modeling of a 2-bit RIS, which serves as a basic building block for subsequent iterations. The choice of a 2-bit configuration allows for four different phase shift states, which are allowing basic manipulation of signal propagation characteristics. This section describes in detail the modeling setup, procedure, and analysis performed to refine design parameters and optimize performance.

2.1.1 Setting up the simulation

Modeling setup includes defining the geometric and material properties of the RIS structure, as well as configuring the modeling environment in the CST Studio software. Key parameters such as the substrate material, dimensions, and the choice of phase shift mechanism (in this case, the RLC diode) are carefully selected to achieve the desired performance characteristics.

2.1.2 Modeling procedure

A systematic approach is used to simulate the 2-bit RIS circuit, which provides an accurate representation of the interaction of electromagnetic waves and the phase manipulation effects. The simulation procedure includes iterative adjustment of design parameters and simulation settings, guided by the general goal of optimizing signal reflection and phase control capabilities.

The design process of a 2-bit RIS requires careful study of the characteristics of its unit cell to ensure optimal performance. To achieve this goal, close attention was paid to the choice of the operating frequency in order to ensure compatibility in the widely available industrial, scientific and medical (ISM) range [22]. Consequently, a frequency of 6.0 GHz was chosen, corresponding to the free and widespread nature of the ISM band, which ensures wide applicability.

A Rogers RO4350B was chosen as the substrate material for the unit cell, having a dielectric constant of 3.66, a loss tangent of 0.0037 and a thermal conductivity of 0.62 [W/K/m] [23]. This choice was made in order to balance the properties of the material and the manufacturability, ensuring proper performance while maintaining the manufacturability of production processes. The RIS structure consisted of three layers: two outer layers consisting of annealed copper with a thickness of 0.035 mm each, and a middle layer made of the Rogers RO4350B substrate with a thickness of 1.54 mm. This three-layer configuration was chosen to facilitate efficient control of electromagnetic waves, while providing mechanical reliability and durability. Parameters such as the size and shape of the RIS elements, as well as the distance between them, have been carefully adjusted to meet the required phase shift requirements and the maximum possibility of surface reconfiguration.

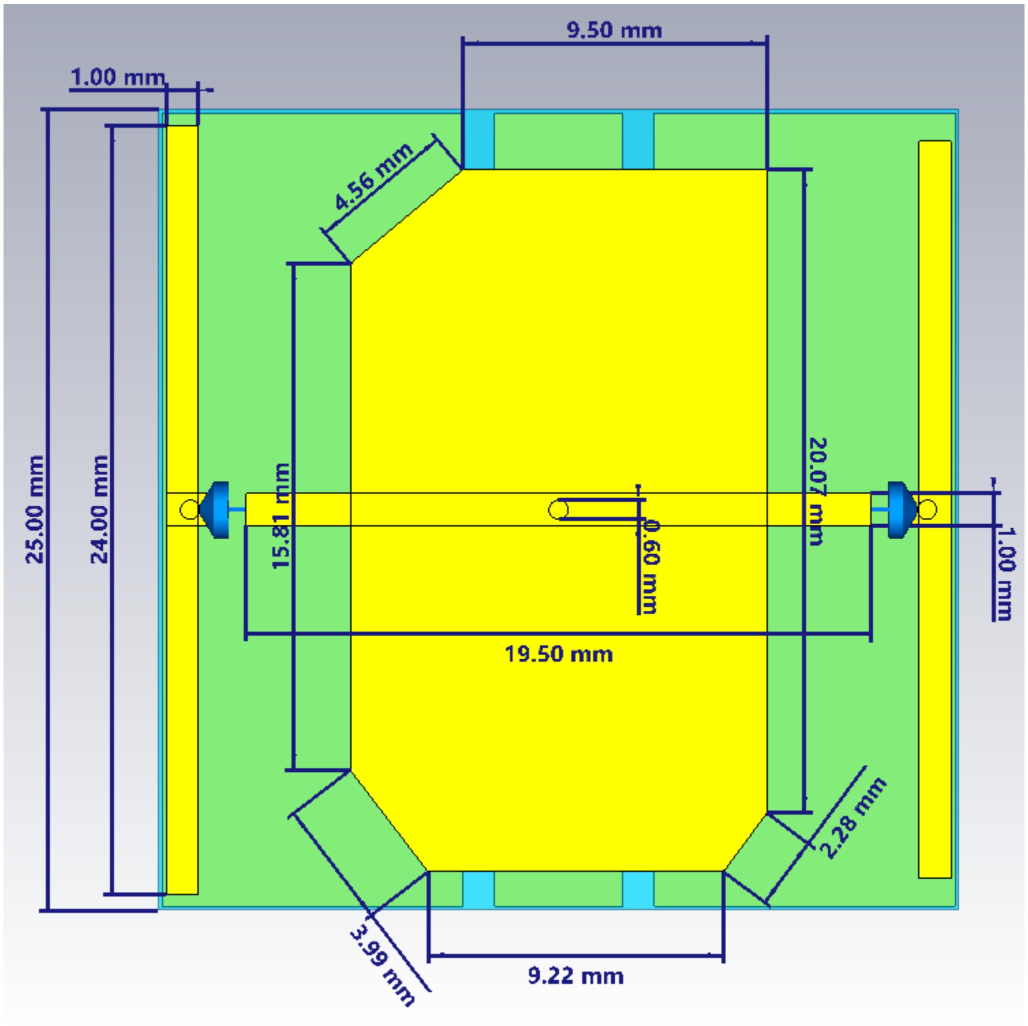


Figure 2.3: Top view of the 2-bit RIS unit cell

The integration of the unit cell with a PIN diode, with the SMPA1320-079LF-203195B model, was crucial for achieving reconfigurability [21]. Each unit cell was equipped with two contact diodes to facilitate the connection between the main unit cell and the ground plane through a metal through hole. This integration made it possible to realize four different states of the unit cell, thereby providing the required reconfigurability necessary for the operation of RIS. To ensure the smooth operation of the elementary element, an offset line was provided connecting the elementary element to the control panel. This connection mechanism provided the necessary control of the PIN diode offset, thereby allowing the states of the unit cell to be manipulated in accordance with the required configuration. The design and dimensions of the 2-bit unit cell can be seen in the schematic images, top and bottom views, Figures 2.1 and 2.2, respectively.

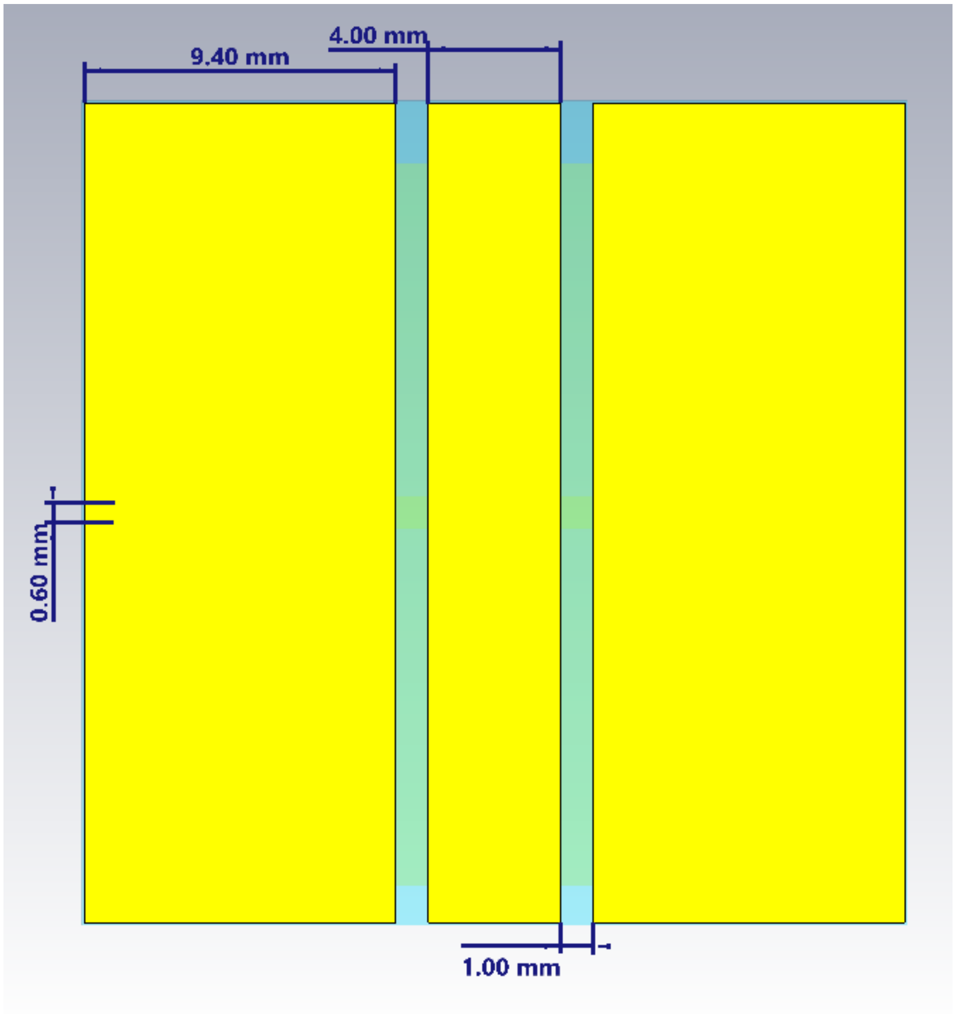


Figure 4.2: Bottom view of the 2-bit RIS unit cell

When designing the 2-bit RIS, close attention was paid to the selection of components and their behavior in various states. The basis for the development was the two-phase PIN diode replacement circuit shown in Figure 2.3 [21]. It has been observed that when the PIN diode is turned ON, it behaves like a series circuit consisting of resistance and inductance. Conversely, when turned OFF, it behaves like a series circuit consisting of capacitance and inductance. In addition, attention is drawn to the use of RLC diodes (resistor-inductor-capacitor) in the configuration of an elementary element. These components play a crucial role in enabling the phase control of the electromagnetic wave through controlled changes in impedance and capacitance. The reasonable selection and configuration of these diodes are important factors in the design process, as they directly affect the performance and operational capabilities of RIS. Therefore, in order to confirm the effectiveness and functionality of the proposed design, careful modeling and analysis of the characteristics of the unit cell is necessary.

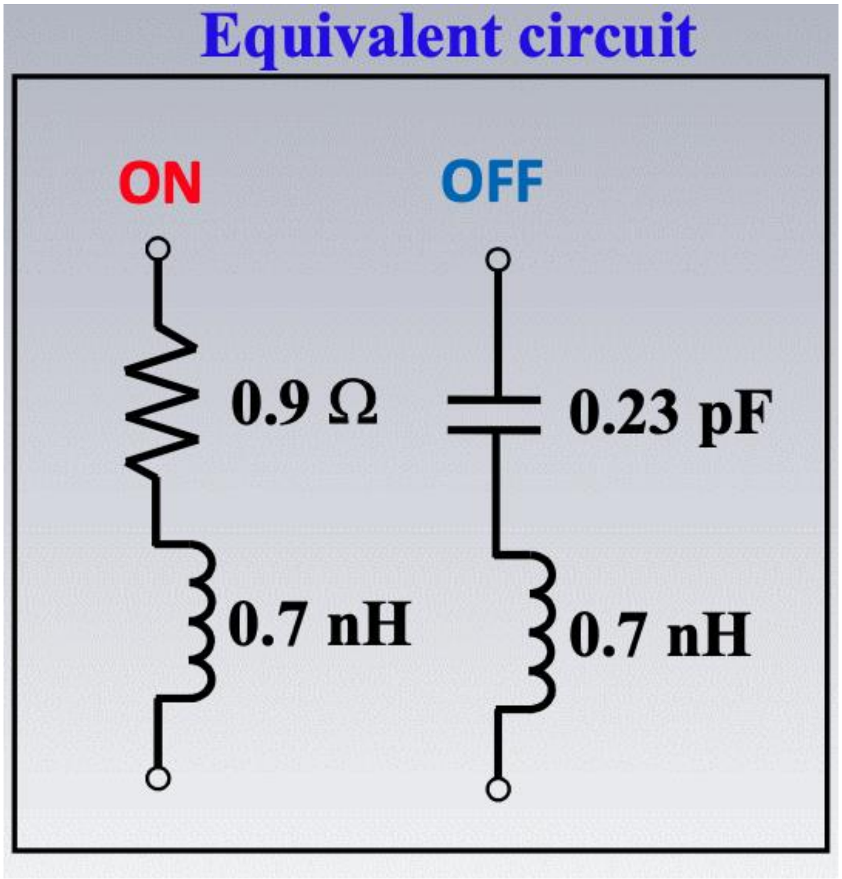


Figure 2.5: Equivalent circuit of the PIN diode [21]

The derivations of the impedance of the PIN diode (equation 2.1) and the reflection coefficient (equation 2.2) were summarized from [21]:

$$Z_{diode}(\omega) = \begin{cases} j\omega L + R & \text{for state ON} \\ \frac{1}{j\omega C} + j\omega L & \text{for state OFF} \end{cases} \quad (2.1)$$

$$\Gamma(\omega) = \frac{Z_{diode}(\omega) - Z_R}{Z_{diode}(\omega) + Z_R} = |\Gamma| e^{j\varphi} \tag{2.2}$$

The central place in the design process was occupied by the definition of a structure capable of providing an appropriate value of radiation resistance (Z_R) to achieve a 180-degree phase change between the ON and OFF states at the target frequency [21]. Achieving this required the development of a unit cell structure that could effectively resonate at a given frequency while minimizing uncontrolled reflections. Usually, a rectangular section about half the wavelength in size is used as a resonant structure. However, in this study, a fractal structure was chosen to achieve a more compact size (a quarter wavelength) without compromising performance [21]. Consequently, the dimensions of the unit cell were set at 25 mm x 25 mm, which allowed to maintain the ratio of performance with a rectangular analog.

When studying the simulation results, it became obvious that at the specified frequency, the reflection value demonstrates a minimal discrepancy between the ON and OFF states of the RIS unit cell. However, there was a noticeable difference in the reflection phase, indicating a 90-degree phase shift between the two states. This phenomenon occurs due to the use of two diodes in the RIS unit cell configuration, which leads to the establishment of four different phase shift states: ON-ON, ON-OFF, OFF-ON and OFF-OFF. This configuration allows RIS to manipulate the phase of electromagnetic waves incident on its surface, thereby facilitating various beam shaping and signal amplification functions in wireless communication systems. The realization of these states with multiple phase shifts is crucial for the adaptability and reconfigurability of RIS in accordance with dynamic environmental conditions and communication requirements. By switching between different phase shift states, RIS can dynamically adjust the propagation characteristics of electromagnetic waves, thereby optimizing transmission, reception and interference reduction in wireless networks.

2.2 Designing 3-bit RIS

The central element of this methodology is the design and simulation of a 3-bit RIS processor capable of achieving eight different phase shift states, each with an interval of 45 degrees. Using advanced electromagnetic modeling tools such as CST Studio, the design process aims to optimize RIS performance in terms of phase manipulation for signal amplification and beam shaping.

2.2.1 Simulation Setup

When designing and modeling a 3-bit RIS with 8 phase shift states, the simulation settings were carefully thought out to accurately reflect the behavior of the structure. The unit cell dimensions for the 3-bit RIS have been set at 16 mm x 16 mm, which is an important decision influenced by the fundamental principles of electromagnetic wave propagation. This decision was based on considering the proportionality of the wavelength to the frequency, especially in the context of the operating frequency of 6 GHz. According to the fundamental relationship between wavelength (λ) and frequency (f) in the propagation of electromagnetic waves, the wavelength is inversely proportional to the frequency expressed by the formula: $\lambda = c/f$, where c is the speed of light in the medium. For a frequency of 6 GHz, the corresponding wavelength can be calculated using this formula. So, electromagnetic waves propagate about 5 cm with a frequency of 6 GHz in free space.

During the modelling of the RIS unit cell, it is important to ensure that its dimensions are small relative to the wavelength of the operating frequency in order to accurately control the phase and amplitude of the incident electromagnetic waves. This consideration is especially relevant for RIS structures operating in the microwave frequency range, where the wavelength sizes are usually on the order of centimeters. Thus, by setting the unit cell dimensions at 16 mm x 16 mm, the RIS structure provides a small size compared to the wavelength of 6 GHz, which allows precise manipulation of electromagnetic waves.

The selected varactor diode of the 1405-79 LF model with dimensions of 1.2 x 0.7 x 0.5 mm^2 [25] was integrated into the design to ensure accurate control of phase shift capabilities. In order to incorporate the electrical characteristics into the simulation model, the technical characteristics of the varactor diode were carefully studied.

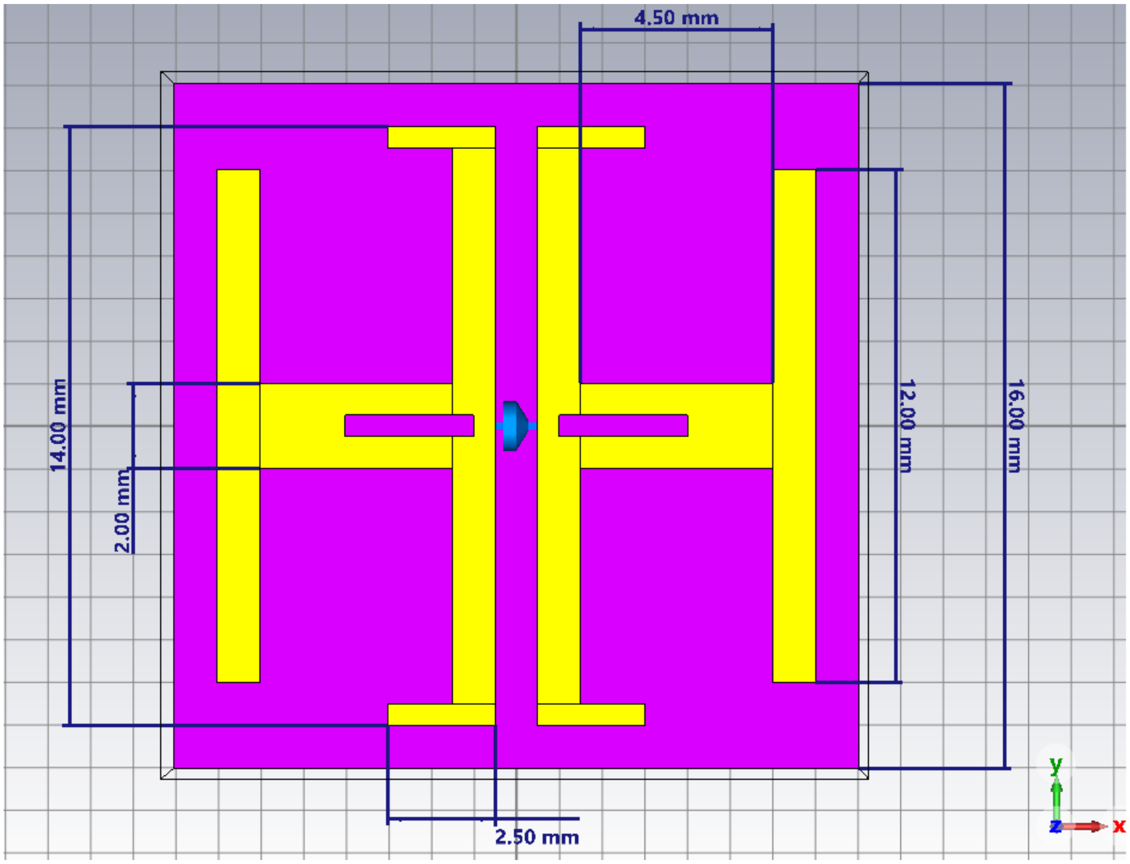


Figure 2.6: Top view of the 3-bit RIS unit cell

The RIS structure consisted of three layers, annealed copper material was used as the upper and lower layers, and the Rogers RO3003 substrate with epsilon of 3, dielectric losses of 0.001 and thermal conductivity of 0.5 [W/K/m] formed the middle layer. That is, the upper and lower levels are made of annealed copper with a thickness of 0.035 mm each, and the substrate level is made of Rogers RO3003 with a thickness of 1.52 mm. These layers were laid in accordance with the specified dimensions obtained in the schematic views from above and below, Figures 2.4 and 2.5, respectively, which ensures that the simulation model conforms to the intended physical design. The dimensions have been carefully entered into the modeling software to accurately display the actual geometry of the shape.

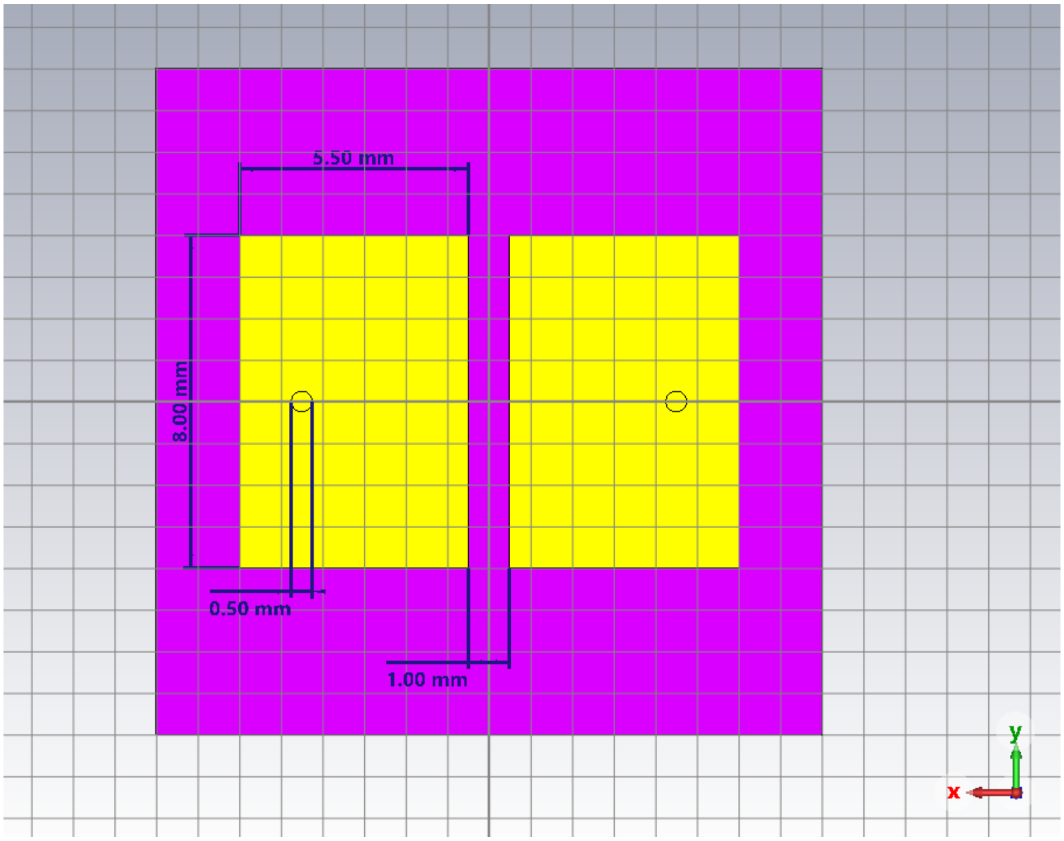


Figure 2.7: Bottom view of the 3-bit RIS unit cell

2.2.2 Simulation Procedure

The modeling procedure began with the creation of a detailed model of the 3-bit RIS structure in the CST Studio software. This included precise determination of the geometry, material properties, and electrical characteristics of each component, including the varactor diode. The electrical properties of the varactor diode specified in the technical description were included in the simulation model to accurately reflect its behavior under various driving conditions [24].

The 1405-79LF varactor diode is a semiconductor device widely used in radio frequency and microwave applications due to its tunable capacitive characteristics. Understanding how this diode works is crucial for its integration into RIS to achieve accurate phase shift capability. The varactor diode operates on the principle of a p-n junction with a reverse bias [25]. In comparison with traditional diodes, which are usually used for rectification, the varactor diode is used mainly because of its capacitance-voltage (C-V) characteristics.

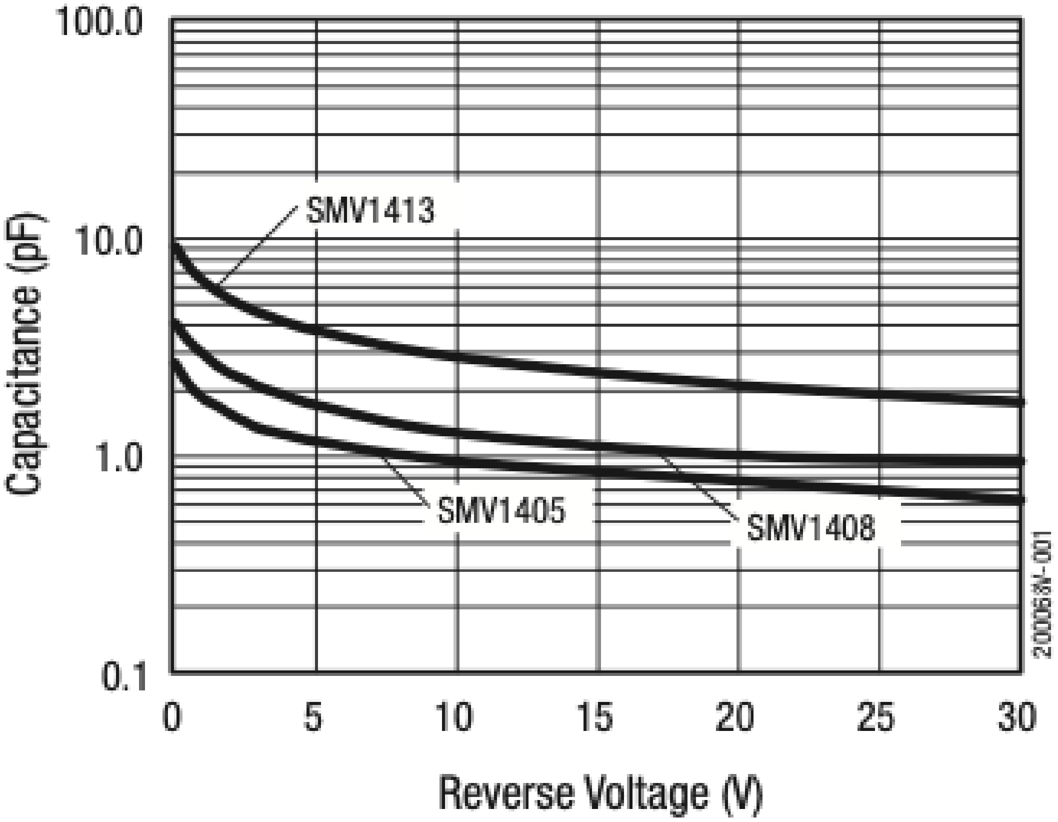


Figure 2.8: Dependence of Capacitance (pF) vs. Reverse Voltage (V) of the 1405-79LF varactor diode [24]

When the varactor diode is shifted in the opposite direction, a discharge region is formed at the junction of p-type and n-type semiconductor materials. This discharge region acts as a dielectric, creating capacitance at the diode terminals. The width of this depletion region and, consequently, the capacitance are inversely proportional to the applied reverse bias voltage [25].

The capacitance of a varactor diode is the most important parameter determining its operation in radio frequency and microwave circuits. The capacitance of the varactor diode varies depending on the applied reverse bias voltage in accordance with a certain dependence. Figure 2.6 shows how the capacitance of a varactor diode changes when the reverse bias voltage at its terminal changes [24]. At lower reverse bias voltages, the width of the depletion region is larger, which leads to an increase in capacitance. As the reverse bias voltage increases, the depletion region narrows, which leads to a decrease in capacitance.

In the context of RIS design, the 1405-79LF varactor diode serves as a key component providing reconfiguration and phase shift. As already mentioned, the varactor diode has three values of passive elements, such as resistance, inductance, capacitance, since capacitance depends on voltage, so the other two elements were installed as specified in the specification, the resistance is 0.3 Ohms, and the inductance is 0.7*10^(-9) H. Adjusting the reverse bias voltage supplied to varactor diodes embedded in RIS elements, the effective capacitance of each diode can be adjusted. This, in turn, modulates the phase of reflected electromagnetic waves incident on the RIS surface. Precise capacitance control of varactor diodes allows precise adjustment of the phase shift introduced by each RIS element, which allows dynamic manipulation of the reflected wavefront. This capability is necessary to optimize the performance of wireless communication systems, including beamforming, signal management, and interference suppression.

Once the model was created, a thorough simulation was performed to analyze the performance of the 3-bit RIS over the entire range of phase shift states. The simulation was carried out using appropriate electromagnetic modeling methods to calculate scattering parameters, reflection coefficients and phase shift characteristics of the RIS structure. During the simulation, various parameters were systematically adjusted to study the impact on RIS performance, such as the bias voltage applied to varactor diodes and the frequency of the incident electromagnetic wave. This iterative approach allowed us to thoroughly explore the design space and optimize the configuration of the RIS to achieve the desired performance indicators.

Chapter 3 – Design Results and Discussion

3.1 Simulation Environment

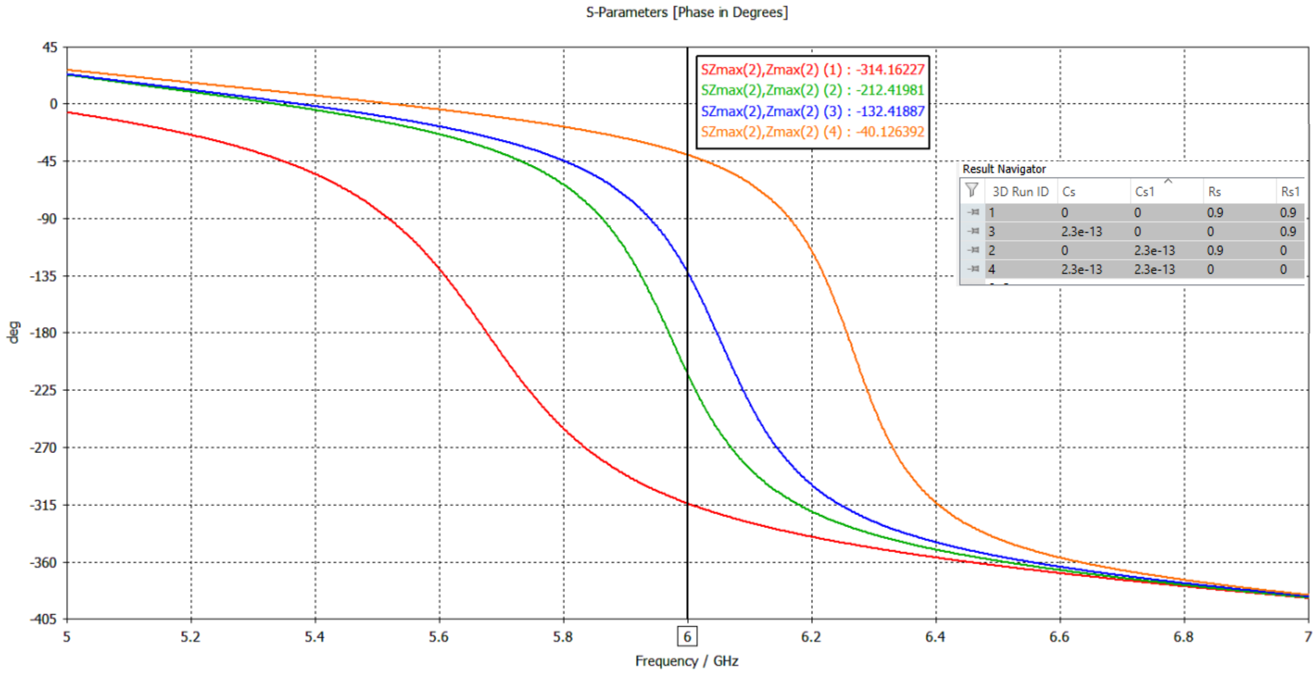
The simulation was performed using CST Studio Suite, a leading electromagnetic simulation software known for its accuracy and versatility. Within the framework of this software, the simulation environment has been carefully designed to simulate the behavior of engineered RIS with maximum accuracy. To capture the subtleties of RIS behavior, the modeling environment has been carefully adapted to consider specific parameters. The surrounding space was characterized by uniform background properties, ensuring consistency across all dimensions with values set to 0.0. This uniformity has contributed to the accurate representation of electromagnetic interactions in the field of modeling.

Boundary conditions played a key role in shaping the simulation results. Each boundary has been carefully configured to reflect real-world scenarios. In this regard, the boundaries in all directions were set as open in order to provide additional space reflecting the characteristic of the infinite propagation of electromagnetic waves. However, in order to prevent unwanted reflections that could distort the results, the Zmin direction was designated as electrically free (E=0), which effectively negates any electromagnetic activity in this direction.

Moreover, to facilitate accurate analysis and interpretation of the RIS behavior, the waveguide port was strategically positioned in the positive Z direction. This port served as an entry and exit point for electromagnetic waves, providing controlled excitation and observation of the interaction of waves with the RIS structure. The location of the port at a normal distance of -0.035 mm provided optimal communication with the simulated environment, increasing the reliability and relevance of the results obtained.

3.2 Performance of 2-bit RIS

The phase shift analysis for the 2-bit RIS involves examining the phase changes introduced by each phase state of the RIS elements. By investigating the phase shift characteristics of the 2-bit RIS, we gain insights into its ability to manipulate the phase of incident electromagnetic waves. This manipulation directly impacts signal propagation and reception characteristics, making it crucial for optimizing the RIS's performance in wireless communication scenarios.



3D Run ID	Cs	Cs1	Rs	Rs1
1	0	0	0.9	0.9
3	2.3e-13	0	0	0.9
2	0	2.3e-13	0.9	0
4	2.3e-13	2.3e-13	0	0

Figure 3.1: S-parameters [Phase in Degrees] results of 2-bit RIS

Figure 3.1 shows the phase shift results obtained from the S-parameters analysis at 6 GHz for different diode states (ON-ON, OFF-ON, ON-OFF, and OFF-ON). These phase shift results can be explained by studying the electrical characteristics of diodes in their respective states. During the ON-ON state, when both diodes are activated, they exhibit a relatively high resistance of 0.9 ohms and zero capacitance. This high resistance causes a significant phase delay of the incident electromagnetic waves passing through the RIS, resulting in a significant negative phase shift of -314.2 degrees. The absence of capacitance minimizes any phase contributions from the capacitive reactance, emphasizing the dominant role of the resistive component in the formation of the phase shift. Furthermore, in the OFF-ON state, one diode is inactive, while the other remains in the on state. An inactive diode with zero resistance and a small capacity of 2.3e-13 F, in fact, acts as a short circuit. This short-circuited diode reduces the overall resistance of the RIS, which results in a lower phase delay compared to the on state, but still results in a significant negative phase shift of -212.4 degrees. Although the capacitance in an inactive diode may make minor phase contributions, they are overshadowed by the influence of the resistive component.

When switching to the ON-OFF state, one diode is activated while the other is inactive. An activated diode with significant resistance and no capacitance leads to a noticeable negative phase shift. Meanwhile, an inactive diode with zero resistance and low capacitance makes a relatively insignificant phase contribution. The combined effect results in a moderate negative phase shift of -132.4 degrees, demonstrating the interaction between the resistive and capacitive components affecting the phase shift. On the OFF-OFF state, when both diodes are inactive, they exhibit negligible resistance and low capacitance. This configuration provides minimal phase delay compared to other states with a slight negative phase shift of -40.1 degrees. Although the capacitive reactance of diodes contributes to the overall phase shift, its effect is relatively insignificant compared to the resistive component.

The observed differences in the phase shift between the diode states in the 2-bit RIS configuration are indeed significant, with each transition resulting in a phase change of approximately 90 degrees at a frequency of 6 GHz. This indicates that the switching mode of the diode has a significant effect on the RIS's ability to manipulate the phase. The transition from the OFF-OFF state to the ON-ON state leads to the most significant change with a phase shift of approximately 274 degrees (-40 degrees to -314 degrees). This transition means activation of both diodes, causing a significant phase change in the reflected electromagnetic wave. Such a drastic change indicates that RIS can effectively control signals when both diodes are in a conductive state.

Furthermore, switching from the OFF-OFF state to the OFF-ON state results in a phase shift of approximately 182 degrees (-40 degrees to -212 degrees). This transition indicates activation of only one diode, which leads to a significant but somewhat less pronounced phase change compared to the ON-ON state. Switching from the ON-ON state to the ON-OFF state results in a phase shift of approximately 182 degrees (from -314 degrees to -132 degrees). This transition means switching off one diode, which leads to a significant phase change, although somewhat less than the transition to the OFF-ON state.

The far-field analysis of the 2-bit RIS provides valuable insights into its radiation characteristics under different diode states. For each of the four cases studied, where the signal was transmitted vertically to the unit cell surface, the far-field monitor was set to 6 GHz. The results, as measured by the Far-field Gain absolute value (Phi=0), reveal distinct radiation patterns and beamforming capabilities associated with the different phase states of the RIS. These results are illustrated in Table 3.1.

Table 3.1: Far-field Gain absolute values (Phi=0) for 4 states

	OFF-OFF	*OFF-ON*	*ON-OFF*	*ON-ON*
Main lobe magnitude	0.336	1.04	1.09	0.23
Main lobe direction [deg.]	30	15	345	330
Angular width (3dB) [deg.]	40.6	46.5	46.6	44.4
Side lobe level [dB]	-0.6	-13	-13.8	-1.9

The OFF-OFF state, where both diodes are inactive, the main lobe magnitude is measured at 0.336, with a direction of 30 degrees and an angular width (3dB) of 40.6 degrees. The presence of side lobes at a level of -0.6 dB indicates a relatively focused radiation pattern. Upon activating one of the diodes, significant changes are observed. 2-bit RIS unit cell far-filed view of the OFF-OFF state is illustrated in Figure 3.2.

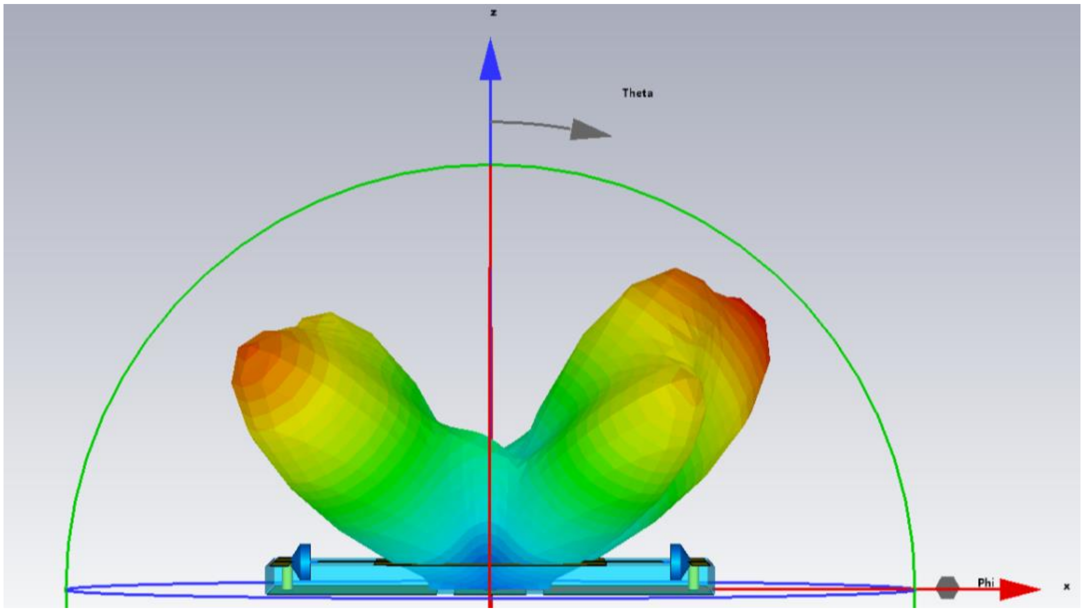


Figure 3.2: Far-filed result of the OFF-OFF state of 2-bit RIS unit cell

The OFF-ON state, the main lobe magnitude increases substantially to 1.04, with a narrower angular width (3dB) of 46.5 degrees, albeit with a slight deviation in the main lobe direction to 15 degrees. This enhancement in gain suggests improved directivity and beamforming capabilities. The far-filed pattern of the OFF-ON state can be seen from Figure 3.3.

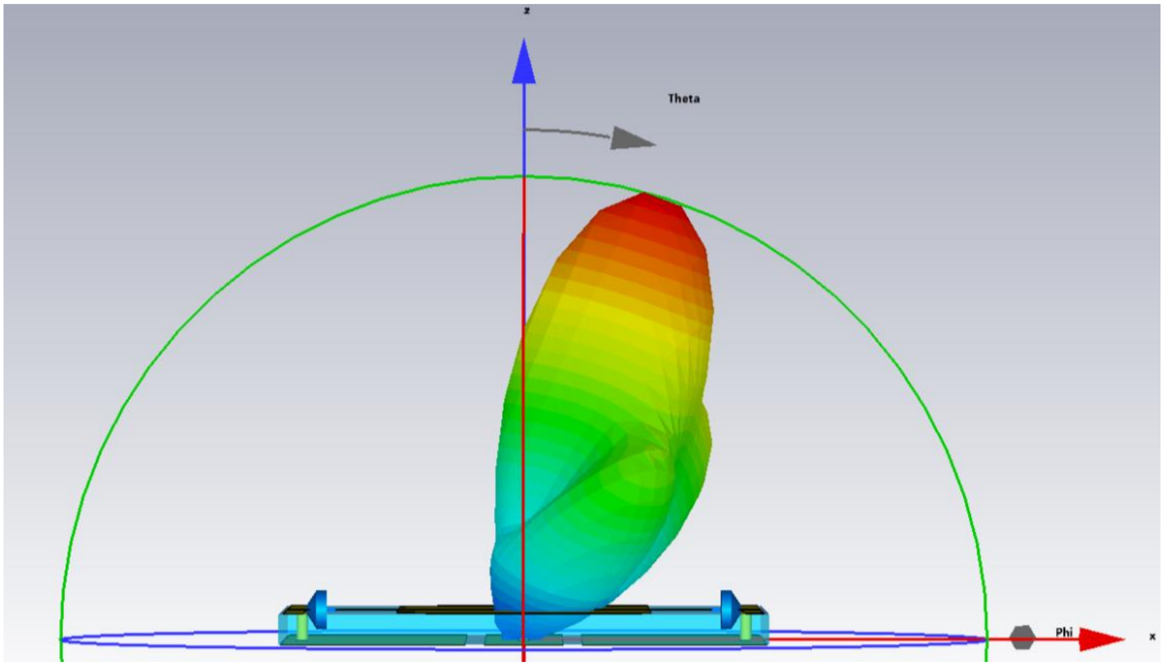


Figure 3.3: Far-filed result of the OFF-ON state of 2-bit RIS unit cell

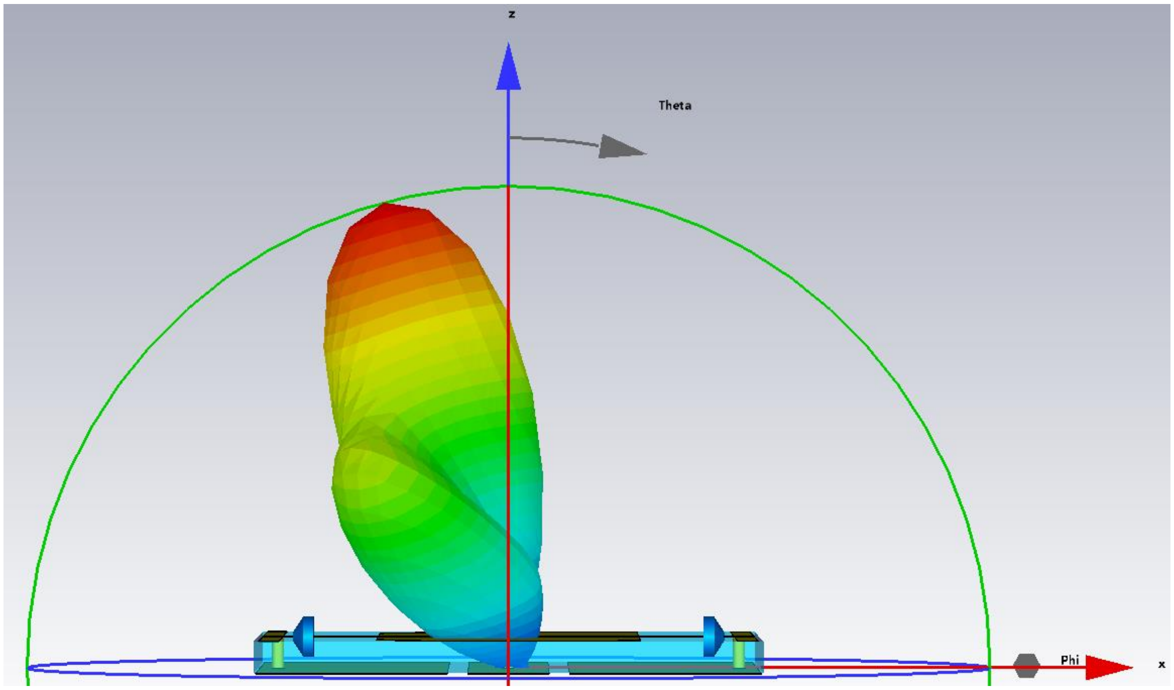


Figure 3.4: Far-filed result of the ON-OFF state of 2-bit RIS unit cell

Moreover, the ON-OFF state, where the first diode is activated while the second remains inactive, the main lobe magnitude further increases to 1.09, with a slight change in the main lobe direction to 345 degrees and a consistent angular width (3dB) of 46.6 degrees. Refer to Figure 3.4

for visualization of the far-field pattern in the ON-OFF state. Notably, the side lobe level remains relatively low at -13.8 dB, indicating maintained radiation focus. However, the ON-ON state, where both diodes are active, the main lobe magnitude decreases to 0.23, with a shift in the main lobe direction to 330 degrees and a wider angular width (3dB) of 44.4 degrees. The presence of side lobes at a level of -1.9 dB suggests a less focused radiation pattern compared to the previous states. Figure 3.5 illustrates the far-field pattern corresponding to the ON-ON state. The contrast between the ON-OFF and OFF-ON states suggests that the activation of either the RLC or varactor diode alone can substantially alter the main lobe magnitude and direction, emphasizing the importance of selective diode control in achieving desired beamforming outcomes.

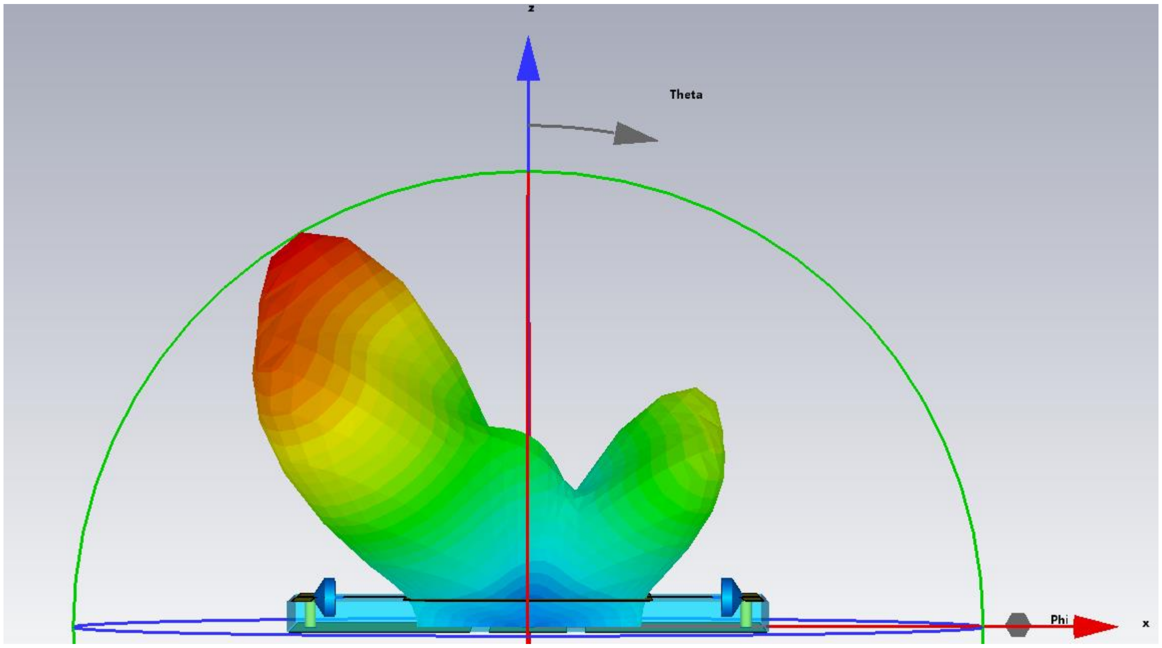
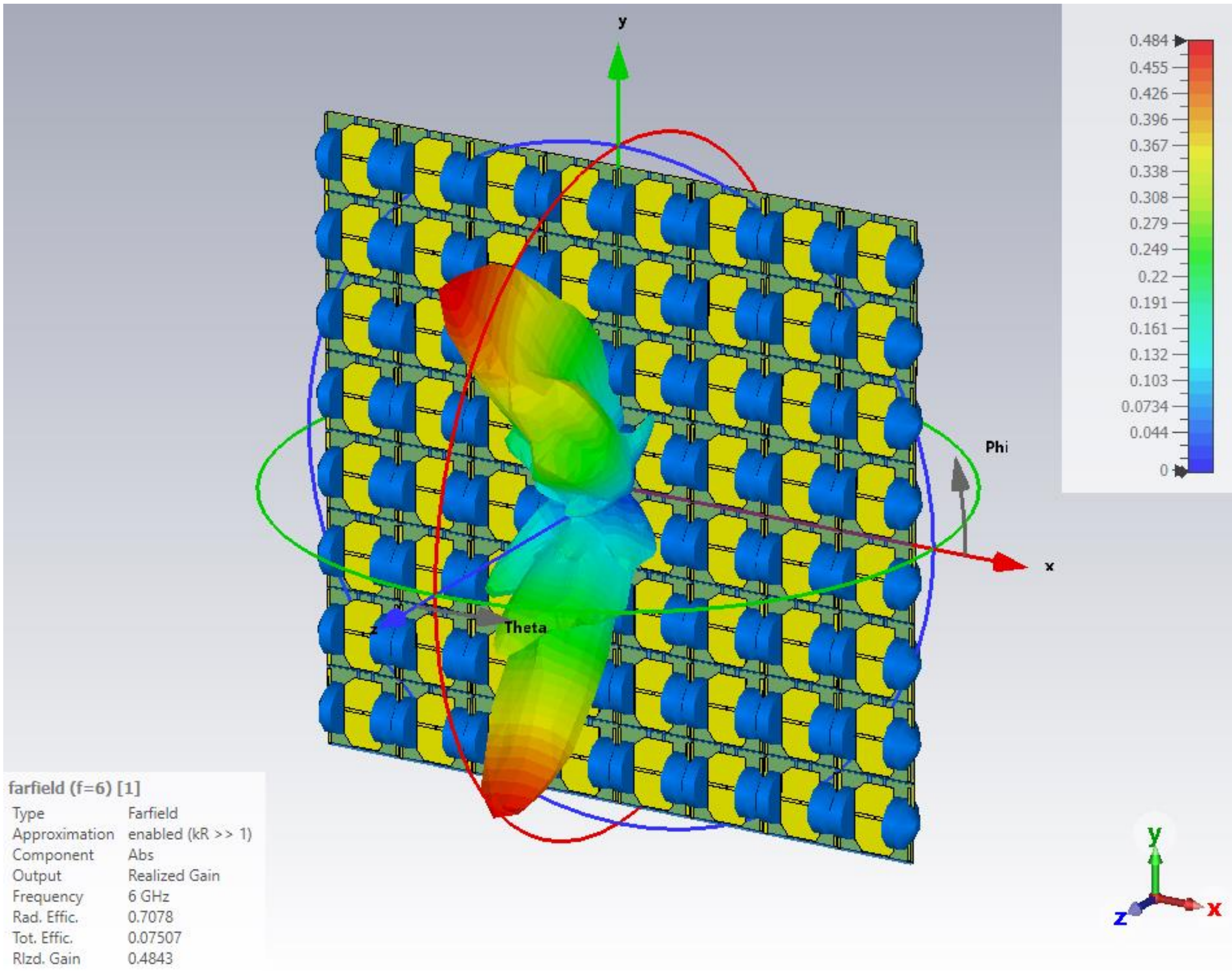


Figure 3.5: Far-filed result of the ON-ON state of 2-bit RIS unit cell

Figures 3.6, 3.7, 3.8 and 3.9 show the results of measurements in the far-field for an 8x8 2-bit RIS matrix in various diode states. These drawings help to demonstrate how the state of the diodes (ON or OFF) in RIS can affect the control of electromagnetic waves, including their direction, focus, and efficiency. The presented data on radiation efficiency, total efficiency and realized gain for each circuit significantly help to understand these effects. Let's analyze and compare them based on these indicators:



farfield (f=6) [1]

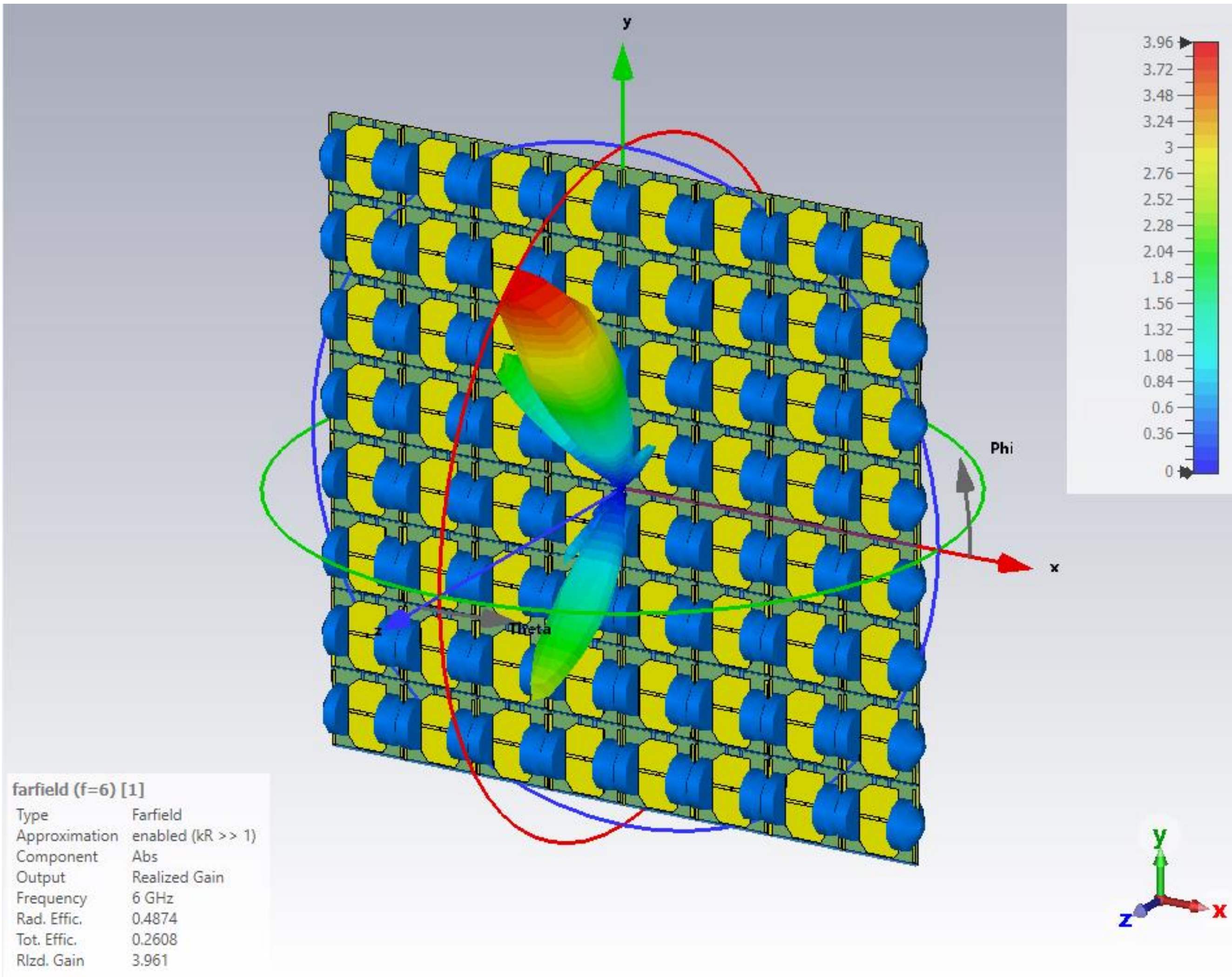
Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Realized Gain
Frequency	6 GHz
Rad. Effic.	0.7078
Tot. Effic.	0.07507
Rlzd. Gain	0.4843

Figure 3.6: Far-field of 8x8 array of OFF-OFF state of the 2-bit RIS

OFF-OFF state:

- Radiation efficiency: 0.7078
- Overall efficiency: 0.07507
- Realized gain: 0.4843

This condition corresponds to a scenario in which both diodes are in the OFF state. A relatively high radiation efficiency indicates that a significant portion of the input power is radiated away, but low overall efficiency and realized gain indicate low overall system performance. This suggests that in the OFF state, although RIS can radiate energy efficiently, its ability to focus and direct this energy in a useful way is limited, resulting in a low gain.



farfield (f=6) [1]

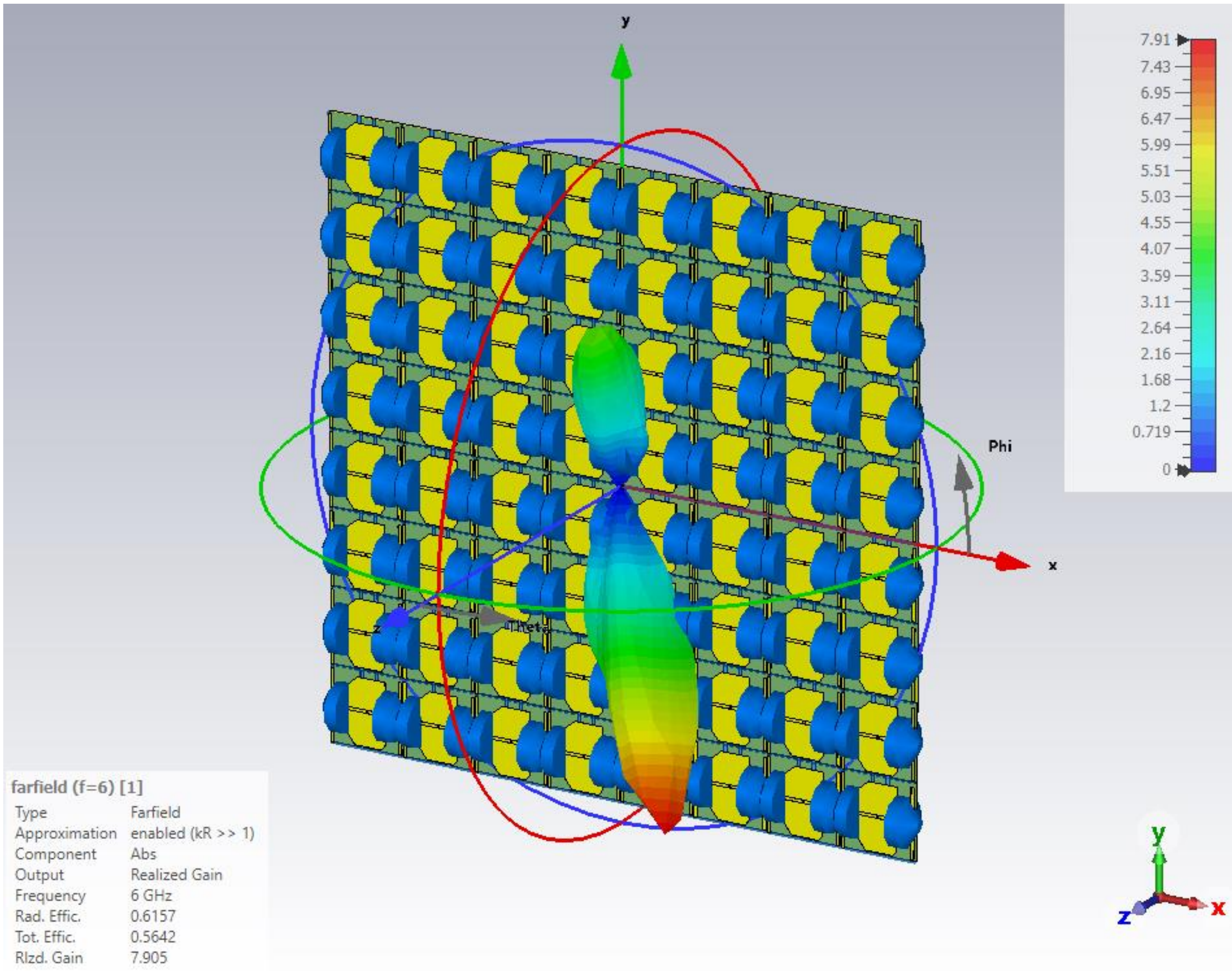
Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Realized Gain
Frequency	6 GHz
Rad. Effic.	0.4874
Tot. Effic.	0.2608
Rlzd. Gain	3.961

Figure 3.7: Far-field of 8x8 array of OFF-ON state of the 2-bit RIS

OFF-ON state:

- Radiation efficiency: 0.4874
- Total efficiency: 0.2608
- Realized gain: 3.961

In this configuration, one diode is OFF and the other is ON. The radiation efficiency is lower than in the OFF state, which means that a smaller part of the input power is emitted. However, a significant increase in overall efficiency and realized gain indicates a much more efficient manipulation of waves, a more efficient direction of energy in the desired direction, which leads to higher gain.



farfield (f=6) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Realized Gain
Frequency	6 GHz
Rad. Effic.	0.6157
Tot. Effic.	0.5642
Rlzd. Gain	7.905

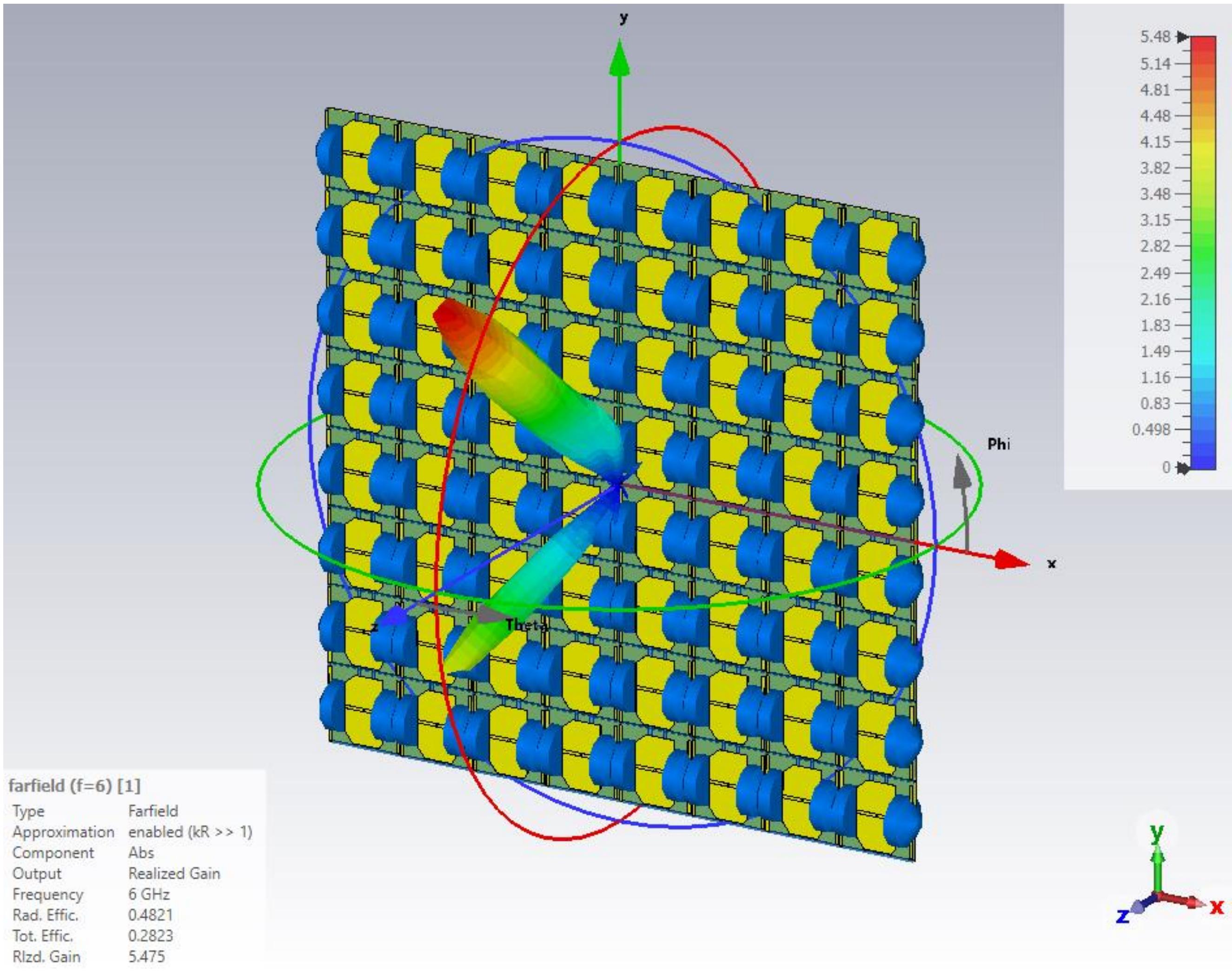
Figure 3.8: Far-field of 8x8 array of ON-OFF state of the 2-bit RIS

ON-OFF state:

- Radiation efficiency: 0.6157
- Overall efficiency: 0.5642

- Realized winnings: 7.905

This configuration, with the first diode ON and the second OFF, demonstrates an improvement in both radiation and overall efficiency compared to the OFF state. The realized gain is the highest among the configurations, which allows optimal manipulation of electromagnetic waves. This state is especially effective for focusing and directing the radiated energy, which is reflected in a significant gain.



farfield (f=6) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Realized Gain
Frequency	6 GHz
Rad. Effic.	0.4821
Tot. Effic.	0.2823
Rlzd. Gain	5.475

Figure 3.9: Far-field of 8x8 array of ON-ON state of the 2-bit RIS

ON-ON state:

- Radiation efficiency: 0.4821

- Overall efficiency: 0.2823
- Realized winnings: 5.475

When both diodes are turned on in this configuration, all efficiency and gain indicators decrease compared to the ON-OFF mode, but they still work better than when the mode is turned OFF, not ON. This suggests that although the ON state can transfer energy more efficiently than when both diodes or one of them is OFF, it is not as efficient as the ON-OFF state.

Based on the results shown in Figures 3.6, 3.7, 3.8, 3.9, the various far-filed views and the implemented amplifications are a direct result of how RIS manipulates electromagnetic waves. With the help of various phase shifts throughout the matrix, RIS can dynamically change the direction and focus of the beam.

3.3 Performance of 3-bit RIS

The study of the RIS field for wireless networks concluded with a key section of our study dedicated to analyzing the performance of 3-bit RIS. This section examines empirical data obtained as a result of our extensive modeling efforts using the CST Studio Suite, a state-of-the-art electromagnetic modeling tool. By carefully manipulating the capacitance values by changing the voltage on the RIS unit cells, we sought to reveal the subtle relationship between the electrical properties of varactor diodes and the resulting phase shifts.

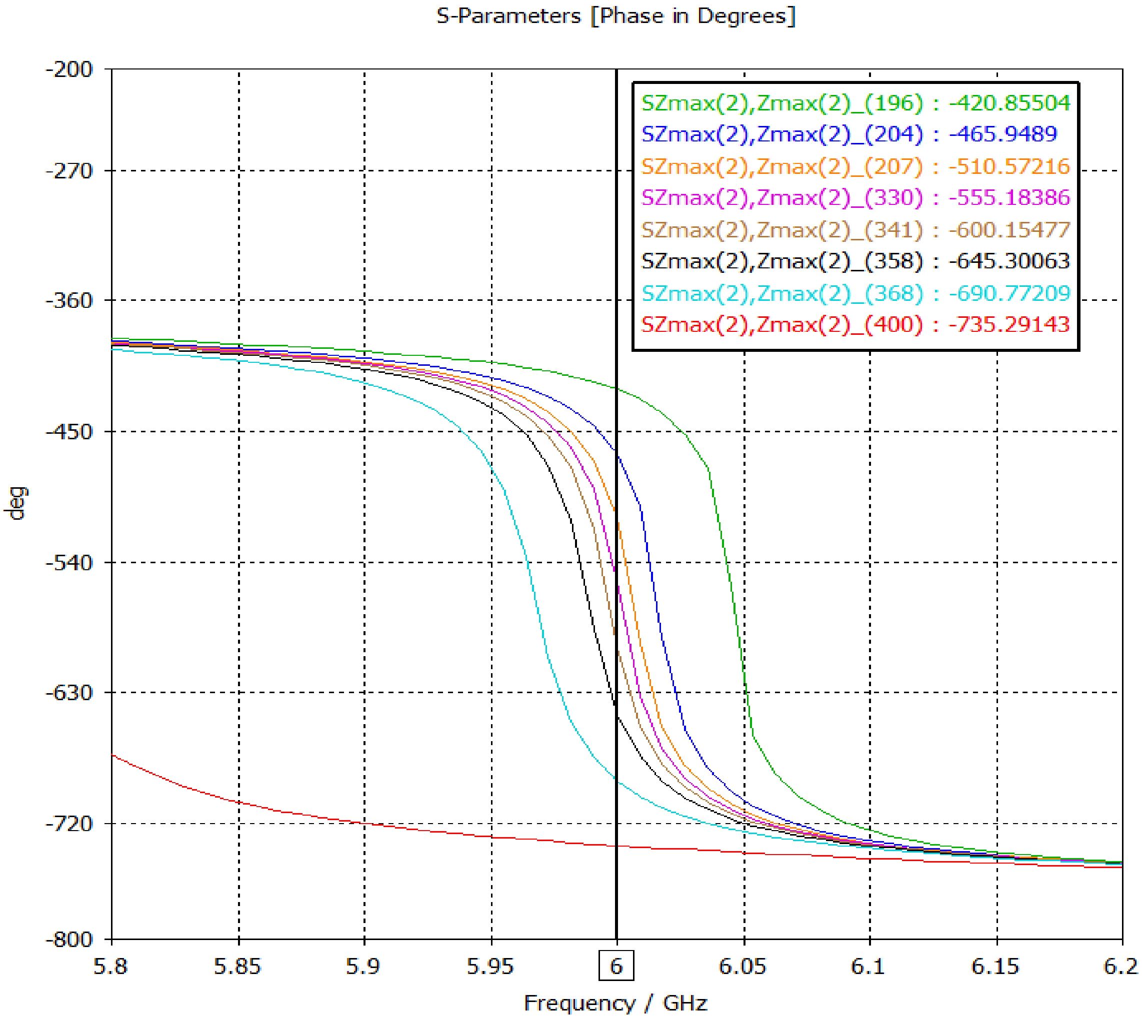
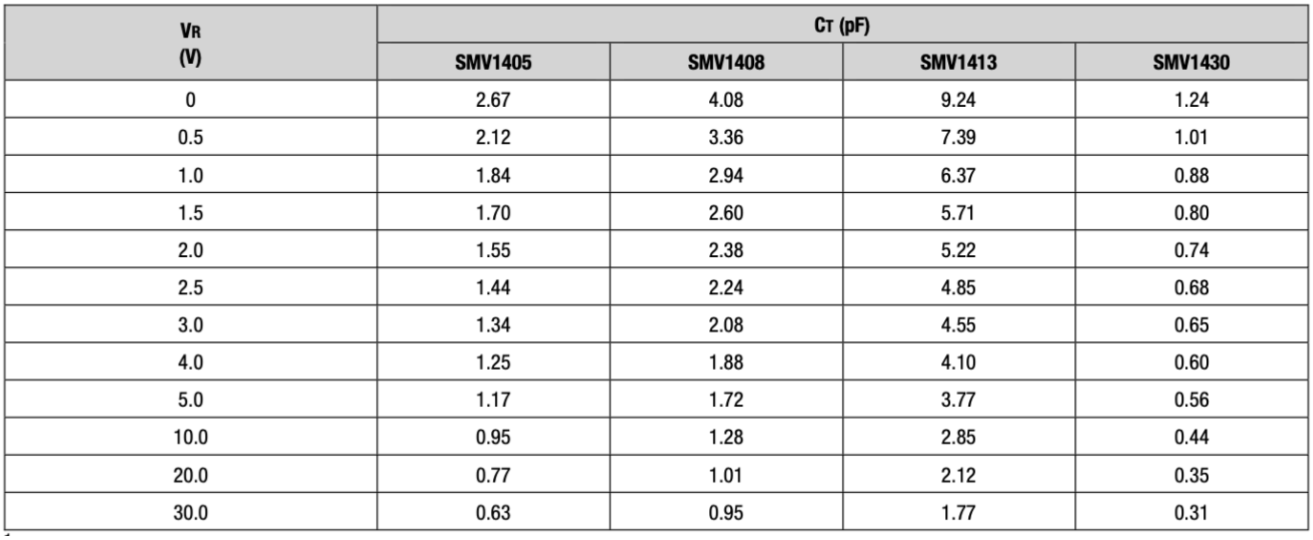


Figure 3.10: Phase shift of 8 states of the 3-bit RIS

Figure 3.10 illustrates the phase shift results obtained from the CST simulation by changing the capacitance values in the 3-bit RIS. This figure is crucial for understanding the dynamic behavior and capabilities of 3-bit RIS. The simulation demonstrates the ability of RIS to manipulate electromagnetic waves using eight different phase shift states, each corresponding to a specific capacitance value induced by a voltage change on varactor diodes. This precise control of phase shifts, varying in increments of about 45 degrees between each state, highlights the potential of RIS in optimizing wireless communication channels. This reveals the subtle interaction between physical properties (such as capacitance) and the resulting electromagnetic phenomena, demonstrating the flexibility and precision of RIS in controlling wavefronts. This capability plays an important role in ensuring adaptive and efficient signal propagation, which is necessary to meet the requirements of next-generation wireless networks such as 5G and later, where dynamic adaptation to the environment is crucial.

Table 3.2: Datasheet of Varactor diode 1405-79 LF [24]



V_R (V)	C_T (pF)			
	SMV1405	**SMV1408**	**SMV1413**	**SMV1430**
0	2.67	4.08	9.24	1.24
0.5	2.12	3.36	7.39	1.01
1.0	1.84	2.94	6.37	0.88
1.5	1.70	2.60	5.71	0.80
2.0	1.55	2.38	5.22	0.74
2.5	1.44	2.24	4.85	0.68
3.0	1.34	2.08	4.55	0.65
4.0	1.25	1.88	4.10	0.60
5.0	1.17	1.72	3.77	0.56
10.0	0.95	1.28	2.85	0.44
20.0	0.77	1.01	2.12	0.35
30.0	0.63	0.95	1.77	0.31

Table 3.2 shows the theoretical conclusions and simulation results in practical reality, describing in detail the technical characteristics of the varactor diode (1405-79 LF) used in the RIS design [24]. The information in the technical description contains important parameters such as the capacitance range and offset voltage requirements, which are crucial for accurate modeling and prediction of the behavior of RIS. This table bridges the gap between theoretical models and real-world implementations by offering specific specifications that serve as the basis for designing and optimizing figs. Using these data, the study ensures that the RIS design is not only theoretically viable, but also practically feasible, bringing the RIS phase shift capabilities in line with the performance characteristics of the selected varactor diodes. Such alignment is crucial to achieve the desired manipulation of electromagnetic waves in real-world deployment scenarios, facilitating

the practical implementation of intelligent reconfigurable surfaces in wireless networks.

Table 3.3: Appropriate Voltage values for Capacitance values

CST value of phase [deg]	**Simulation Capacitance value (pF)**	**Difference of phase [deg]**	**Voltage (V)**
420.85504	0.728889		22.4708
465.9483	0.771717	45.09326	19.5655
510.57216	0.787778	44.62386	18.536
555.18386	0.796571	44.6117	17.9871
600.15477	0.80472	44.97091	17.488
645.30063	0.818938	45.14586	16.6398
690.77209	0.856779	45.47146	14.5259
735.29143	2.67	44.51934	0.0036

Table 3.3 has been carefully compiled based on data extracted from the varactor diode specification presented in Table 3.2. It defines the required voltage offset values required to achieve the desired capacitance levels for 3-bit RIS, thereby facilitating the eight different phase shift states shown in Figure 3.10. This table is crucial for translating theoretical developments into practical applications, providing a simple guide to the design of electronic RIS controls. It shows the direct relationship between the applied voltage and the capacitance of varactor diodes, which gives an idea of the practical aspects of the RIS configuration to ensure optimal performance. This ratio is fundamental for the dynamic reconfigurability of RIS, which allows real-time correction of electromagnetic wave manipulation using precise electronic control. Such detailed management paves the way for the creation of highly adaptive wireless networks that can effectively eliminate

problems such as interference and signal attenuation, thereby increasing communication reliability and bandwidth.

The results demonstrate a deep understanding of the interaction between electronic control (via voltage bias) and electromagnetic behavior (via phase shifts), supported by practical considerations (using varactor diode specifications). This combination of theoretical understanding, simulation-based validation, and a practical implementation strategy highlights the potential of RIS technology to revolutionize wireless communications through dynamic adaptive control of signal propagation paths.

Chapter 4 – Further Advancements

4.1 Prototype of RIS

The 3-bit RIS prototype, developed in collaboration with the engineering faculty of a university, was meticulously designed and printed following with provided methodology. This process included detailed simulation settings to emulate the behavior of the RIS accurately. The prototype features a unit cell size of 16mm x 16mm, optimized for electromagnetic wave propagation. It incorporates a 1405-79 LF varactor diode for precise phase shift control. Comprising three layers, the structure utilizes annealed copper for the top and bottom layers and a Rogers RO3003 substrate for the middle layer, ensuring effective performance characteristics.

Figure 4.11: 3-bit RIS prototype view

The dimensions of 3-bit RIS prototype was fabricated using the Gerber file. This approach facilitated the precise translation of the prototype's design into a physical form, ensuring the accurate implementation of the unit cell dimensions, integration of the varactor diode, and the layered structure comprising annealed copper and Rogers RO3003 substrate. During the printing process of the 3-bit RIS prototype, the design contains a feature known as a voltage via. This via serves as a bridge connecting the top and bottom layers of the prototype. It is meticulously created by drilling through the substrate, followed by melting copper into the drilled via. This method ensures a reliable electrical connection between the layers, which is essential for the prototype's functionality and the precise control over the phase shifts facilitated by the integrated varactor diode. Visual representations can be seen from Figures 4.1 and 4.2.

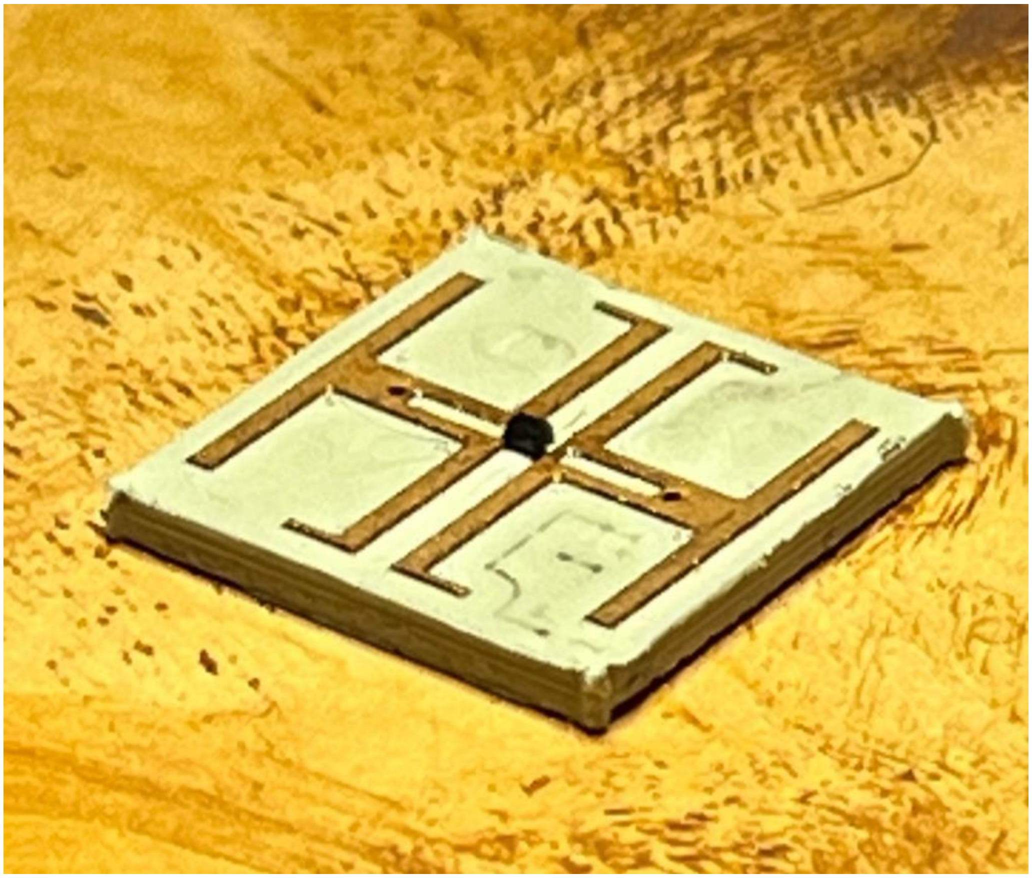


Figure 4.12: Unit cell view of 3-bit RIS

4.2 Further Steps

Access to an anechoic chamber is required to fully evaluate and refine the 3-bit RIS prototype. This controlled environment is crucial for accurately measuring RIS performance by eliminating external electromagnetic interference. The following steps include:

1. Anechoic chamber testing: conducting comprehensive tests to measure the prototype's phase shift capabilities, reflection efficiency, and overall performance in an interference-free environment.
2. Optimization based on test results: data analysis to identify any discrepancies between the simulated forecasts and the actual characteristics. This analysis will help adjust the design, material selection, or assembly process.
3. Iterative design improvement: making design changes based on test results. This iterative process aims to increase RIS efficiency, minimize losses, and optimize phase shift accuracy.
4. Application Integration and Testing: exploring the possibilities of integration with real-world applications, such as wireless communication systems or radars, to assess the practical usefulness and performance of RIS in the workplace.
5. Scalability and Productivity: solving the challenges of expanding RIS production to a wider application, ensuring that production processes can maintain the precision and quality inherent in the prototype.

This comprehensive approach, from prototype printing to further development stages, aims to ensure that the 3-bit RIS not only meets theoretical expectations, but also surpasses them in practical application, paving the way for its integration into future electromagnetic systems.

Chapter 5 - Conclusion

In this master's thesis, we explored the innovative design and implementation of RISs to improve wireless network performance. Our journey began with a comprehensive overview of the theoretical foundations and modern achievements in this field, which laid the foundation for our experimental research. By studying the electromagnetic principles underlying RIS technology, we have developed and modeled advanced RIS models capable of dynamic reconfiguration, thereby significantly improving signal propagation and network efficiency.

Our contributions to research are diverse. We have implemented new RIS architectures combining active diode elements that allow you to adjust surface properties in real time. Through careful modeling, we have demonstrated the effectiveness of 2-bit and 3-bit RIS circuits in controlling electromagnetic waves to improve communication results. Our results highlight the potential of Smart RIS to revolutionize wireless communications by offering ways to overcome traditional network limitations and open a new era of connectivity.

The practical significance of our work goes beyond the academic sphere and promises significant progress in the deployment of 5G and other wireless networks. By creating more efficient and adaptable network infrastructures, Smart RIS technology is coming to the fore in next-generation wireless communication systems. This thesis not only contributes to the academic discourse on RIS, but also lays the foundation for future innovations in this field.

In conclusion, our study confirms the transformative potential of intelligent reconfigurable surfaces to enhance wireless network performance. Through innovative design, careful modeling and analysis, we have demonstrated the capabilities of RIS technology in solving modern communication problems. As we look to the future, it becomes clear that the ongoing research and development of intelligent RIS will play a key role in shaping the evolution of wireless networks, promising to make the world more interconnected and efficient.

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