



**REPUBLIC OF TURKEY
ADANA ALPARSLAN TÜRKEŞ SCIENCE AND TECHNOLOGY
UNIVERSITY**

**GRADUATE SCHOOL
ELECTRICAL AND ELECTRONIC ENGINEERING DEPARTMENT**

**METAMATERIAL-INSPIRED ANTENNA DESIGNS FOR IoT/5G
APPLICATIONS**

Duygu Nazan GENÇOĞLAN

Ph.D.

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ADANA, 2023

DECLARATION OF CONFORMITY

In this thesis study, which was prepared following the thesis writing rules of Adana Alparslan Türkeş Science and Technology University Institute of Graduate School, I declare that I provide all the information, documents, evaluations and results in accordance with scientific ethics and moral codes without resorting to any means or assistance that would be contrary to scientific ethics and traditions. I also declare that I refer to all of the articles I used in this study with appropriate references and accept all moral and legal consequences if a situation is found contrary to my statement regarding my work.

.../.../20..

[Signature]

Duygu Nazan GENÇOĞLAN

ÖZET

IoT/5G UYGULAMALARI İÇİN METAMALZEMEDEN ESİNLENEN ANTEN TASARIMLARI

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Nesnelerin İnterneti (IoT) ve Beşinci Nesil (5G) ağlarının bir araya gelmesi, kompakt cihazlarda ve yoğun ağ ortamlarında verimli anten tasarımlarının geliştirilmesine olan ihtiyacı artırmıştır. Bu tez, özellikle 6 GHz altı uygulamalara odaklanarak frekansı yeniden yapılandırılabilir metamalzeme tabanlı antenlerin derinlemesine incelenmesini sunmaktadır. Bu çalışmada temel amaç, metamalzeme yapılarının özelliklerinden faydalanan, kompaktlık ve frekans yeniden yapılandırılabilirliği sağlayan yeni anten tasarımları geliştirmektir. Kapsamlı bir literatür taraması yoluyla tez, metamalzeme tabanlı antenlerin ve Bölünmüş Halka Rezonatörü (SRR) yapılarının IoT ve 5G bağlamlarında anten performansı üzerindeki etkilerini incelemektedir. Çalışma, frekansı yeniden yapılandırılabilir antenler için yeni tasarımlar önermekte ve incelemektedir. Tasarımlar, SRR'ler dahil olmak üzere çeşitli rezonatörleri birleştirmekte ve antenlerin elektriksel uzunluğunu değiştirmek için PIN diyotları, SPDT anahtarları ve bakır yol değişiklikleri gibi farklı anahtarlama mekanizmalarını kullanmaktadır. Geri Dönüş Kaybı, Işıma Deseni ve Işıma Verimliliği gibi önemli anten parametreleri 6 GHz altı aralıkta analiz edilmektedir. Önerilen frekansı yeniden yapılandırılabilir antenlerin prototipleri de deneysel olarak test edilmektedir. Simülasyon ve deneysel sonuçlar, önerilen tasarımların etkinliğini doğrulayarak önemli ölçüde boyut küçültme, yüksek verimlilik ve dinamik frekans uyarlanabilirliği ortaya koymaktadır. Böylece bu çalışma, frekans yeniden yapılandırması, kompaktlık ve ışıma verimliliği açısından kablosuz haberleşme sistemlerindeki önemli boşlukları gidermektedir.

Anahtar Kelimeler: 5G, Ayırık Halka Rezonatörü (AHR), IoT, Metamalzemeler, Yeniden Yapılandırılabilir Antenler.

ABSTRACT

METAMATERIAL-INSPIRED ANTENNA DESIGNS FOR IoT/5G APPLICATIONS

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The advances on the Internet of Things (IoT) and Fifth Generation (5G) networks has increased the need for efficient antenna designs in compact devices and dense network environments. This thesis presents an in-depth investigation of frequency reconfigurable metamaterial-based antennas, focusing particularly on applications below 6 GHz. The main purpose in this study is to develop novel antenna designs that utilize the properties of metamaterial structures, achieving compactness and frequency reconfigurability. Through an extensive literature review, the thesis examines the effects of metamaterial-based antennas and Split Ring Resonator (SRR) structures on antenna performance within the IoT and 5G contexts. The study proposes and investigates novel designs for frequency reconfigurable antennas. The designs incorporate diverse resonators, including SRRs, and employ different switching mechanisms such as PIN diodes, SPDT switches, and copper path alterations to modify the electrical length of the antennas. Significant antenna parameters such as Return Loss, Radiation Pattern and Radiation Efficiency are analyzed in the sub-6 GHz range. Prototypes of the proposed frequency reconfigurable antennas are also tested experimentally. The simulation and experimental results validate the efficacy of the proposed designs, demonstrating significant size reduction, high efficiency, and dynamic frequency adaptability. Thus, this study addresses the important gaps in wireless communication systems in terms of frequency reconfiguration, compactness and radiation efficiency.

Keywords: 5G, IoT, Metamaterials, Reconfigurable Antennas, Split-Ring Resonators (SRRs).

Dedication

to My Beloved Family: Dudu, Mustafa, Ezgi & Özge

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LIST OF ABBREVIATIONS

ADS	: Advanced Design System (Simulation program)
16QAM	: 16 Quadrature Amplitude Modulation
64QAM	: 64 Quadrature Amplitude Modulation
1G	: First Generation
2G	: Second Generation
3D	: Three-dimensional
3G	: Third Generation
4G	: Fourth Generation
5G	: Fifth Generation
6G	: Sixth Generation
BW	: Bandwidth
CDMA	: Code Division Multiple Access
CDMA2000	: 3G mobile technology standard
CST	: Computer Science Technology (Antenna Design Program)
DC	: Direct Current
DSP	: Digital Signal Processor
EDGE	: Enhanced Data rates for GSM Evolution
EDX	: Energy Dispersive X-Ray Analysis
FDMA	: Frequency Division Multiple Access
FDTD	: Finite Difference Time Domain
FEM	: Finite Element Method
FEM-BI	: Finite Element Method – Boundary Integral
Gbit	: Gigabit
Gbps	: Gigabit per second
GHz	: Gigahertz
GPRS	: General Packet Radio Service
GSM	: Global System for Mobile Communication
IMT	: International Mobile Telecommunications
IMT-2000	: International Mobile Telecommunication-2000
IoT	: Internet of Things
ITU	: International Telecommunication Union

Kbps	: Kilobit per second
kHz	: Kilohertz
LTE	: Long Term Evolution
LTE-A	: Long Term Evolution-Advanced
M2M	: Machine to Machine Communication
Mbit	: Megabit
MEMS	: Micro-Electro-Mechanical Systems
MHz	: Megahertz
MIMO	: Multiple Input Multiple Output
MLFMM	: Multi-Level Fast Multipole Method
mm	: Millimeter
MOM	: Method of Moments
MOM-TD	: Method of Moments in Time Domain
<i>n</i> H	: Nanohenry
OFDMA	: Orthogonal Frequency Division Multiple Access
PCB	: Printed Circuit Board
PCS	: Personal Communication Systems
<i>p</i> F	: Picofarad
QPSK	: Quadrature Phase Shift Keying
RF	: Radio Frequency
RL	: Return Loss
SC-FDMA	: Single Carrier-Frequency Division Multiple Access
SDMA	: Spread Spectrum Multiple Access
sec	: Second
SMS	: Short Message Service
TDMA	: Time Division Multiple Access
THz	: Terahertz
UMTS	: Universal Mobile Telecommunications System
VLAN	: Virtual Local Area Network
VSWR	: Voltage Standing Wave Ratio
W-CDMA	: Wideband Code Division Multiple Access
Wi-Fi	: Wireless Fidelity
WiMAX	: Worldwide Interoperability for Microwave Access

LIST OF SYMBOLS

c	: Speed of light
c_0	: Speed of light in vacuum
C	: Capacitance
dB	: Decibel
dB _i	: Decibel isotropic
$\mathbf{E}$	: Electric Field
ε	: Permittivity
ε_0	: Electrical permittivity of free space
ε_{eff}	: Effective dielectric constant (or electrical permittivity)
ε_r	: Relative permittivity, dielectric constant
$\mathbf{H}$	: Magnetic Field
k	: Wave number
L	: Inductance
μ	: Permeability
μ_0	: Magnetic permeability
n	: Refractive index
n_{eff}	: Effective refractive index
S_{11}	: Reflection coefficient
λ	: Wavelength
λ_0	: Wavelength of free space
Ω	: Ohm

1. INTRODUCTION

1.1. The Evolution of Wireless Communication

The evolution of wireless communication has been driven by the need to meet escalating user demands for mobility, data transmission speed, and network capacity [1]. This has required rapid growth and upgrades to cellular networks and mobile devices. First Generation (1G), the first analog cellular systems were introduced in the 1980s based on frequency modulation and frequency division multiple access techniques [2]. 1G was limited to low data rate voice transmission over circuit switched networks using frequencies around 800-900 MHz with 30 kHz channel capacity [3]. The antennas used were basic single band whip monopoles protruding from devices [2]. 1G systems had very limited data transmission capabilities and low security due to the analog technology [1]. Second Generation (2G) cellular systems emerged in the 1990s, providing both voice and data services through standards like GSM. Data rates increased to up to 150 kbps with introduction of General Packet Radio Service (GPRS) [3]. Further enhancements like Enhanced Data rates for GSM Evolution (EDGE) pushed rates to 384 kbps. 2G uses digital modulation techniques like Time Division Multiple Access and Code Division Multiple Access which improved spectrum efficiency over analog 1G [1]. The transition to digital signals reduced power consumption, but required strong signal coverage for phones to operate [4]. While antennas remained external whip monopoles initially, some 2G phone manufacturers integrated internal antennas, enabling more compact form factors like clamshell designs [2]. Third Generation (3G) address the limited data capacity of 2G, third generation (3G) cellular systems were developed in the late 1990s and early 2000s. Standards like IMT-2000 provided theoretical download speeds up to a few Mbps [5]. Technologies like W-CDMA, WiMAX and CDMA2000 enabled advanced services like high-speed internet access, high quality video calls and multimedia streaming. 3G phones integrated more complex internal multi-band antennas to support multiple frequencies and higher bandwidths [2]. Fourth Generation (4G) emerged in the late 2000s and early 2010s in the form of Long-Term Evolution (LTE) standards. LTE uses advanced modulation schemes like QPSK, 16QAM and 64QAM to deliver peak theoretical downlink speeds up to 1 Gbps for low mobility users and 500 Mbps uplink [6]. Orthogonal FDMA is used for downlink multi-access while Single Carrier FDMA is used for the uplink. 4G also employs multiple antenna techniques like MIMO to enhance speeds. To maintain connectivity across different generations of networks, 4G devices also maintain backwards compatibility with older 3G

bands, as 4G infrastructure coverage is still developing [6]. In summary, each generational shift in wireless technology has delivered step function advances in data transmission speeds, network capacity, and device antenna integration in order to meet escalating user demands [1]. However, supporting multiple generations during transitional periods poses ongoing design and deployment challenges. Further innovations in 5G and beyond aim to continue advancing mobile broadband capabilities. Figure 1.1 shows the frequency band allocation used in wireless communication systems from 1G to 4G.



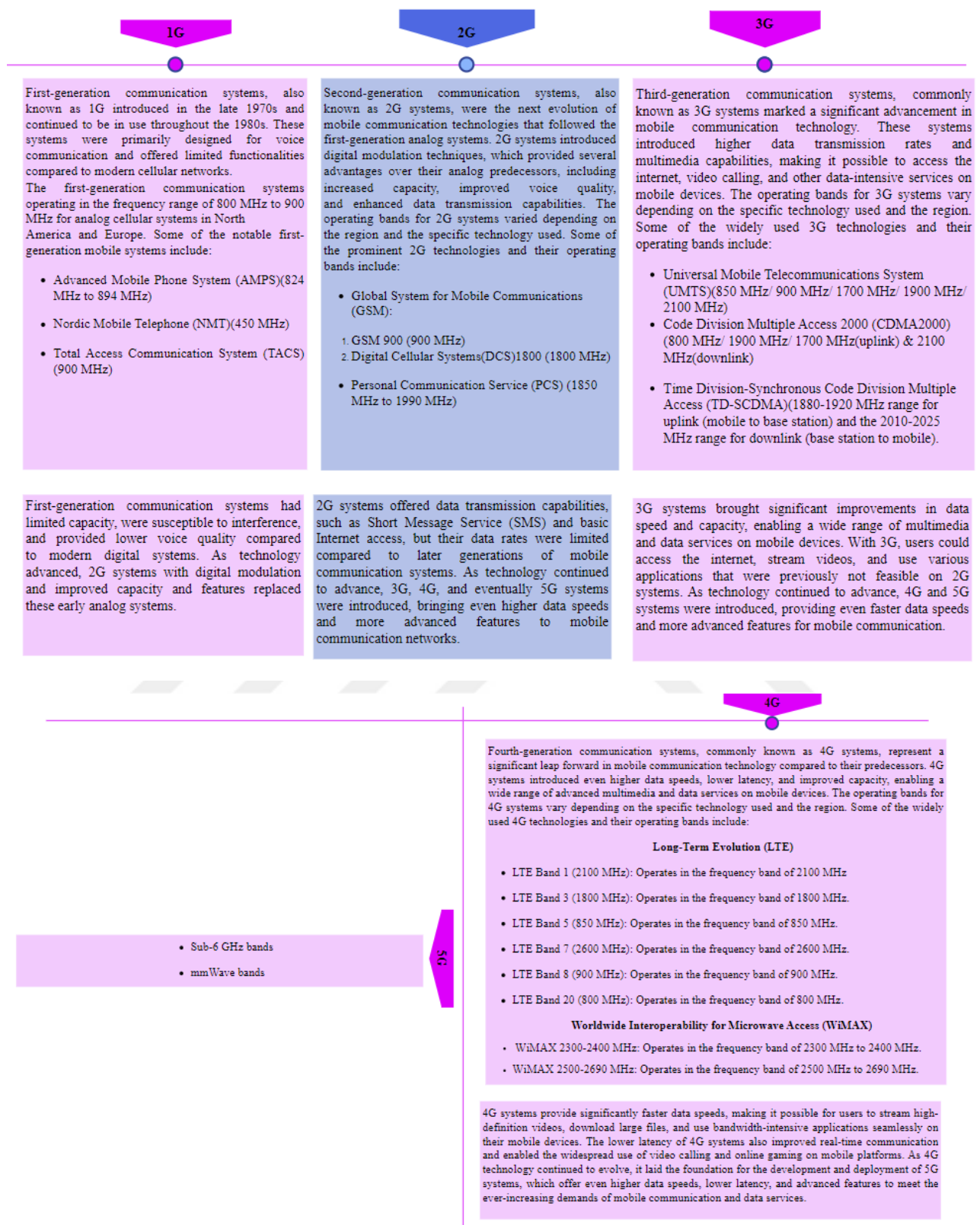


Figure 1.1. Frequency allocation for wireless communication systems [1-6].

The fourth generation (4G) is not sufficient and efficient enough to meet the challenges of multiple device connections, high data speeds, increased bandwidth, low latency, and low noise requirements. To overcome these challenges, the fifth generation (5G) is a promising technology that is expected to revolutionize wireless technology [7]. The 5G mobile network aims to address the limitations of previous cellular standards and serve as a potential enabler for the Internet of Things (IoT) in the future [7, 9-11]. IoT allows machine-to-machine (M2M) communication between heterogeneous devices without human intervention [11, 12]. Enabling 5G networks to connect everything wirelessly from household appliances to daily consumer devices is expected to be the key driver for IoT technology, especially in consumer electronics, building security, and automation. It is predicted that a significant part of the consumer electronics segment will be dominated by wearable technology applications. The aim with 5G is to create a solution that integrates the existing frequencies that are already in use. Therefore, a wide range of frequency bands is being considered, and efforts are being made to develop a solution that covers the frequencies currently in use. The 5G standards shaped during the 2019 European 5G Observatory meeting, conducted by the International Telecommunication Union (ITU) under the International Mobile Telecommunications (IMT) program, also cover the frequencies used by 4G. The ITU intends to create a standard that will work across low (<3 GHz), mid (3-6 GHz), and high (>6 GHz) frequencies [13-18]. Studies are being conducted to explore the use of known microwave frequencies, along with millimeter wave and Terahertz frequencies, as standard frequencies for 5G communication systems [19]. Figure 1.2 presents the allocated frequencies in the 5G planning of some countries. These are just a few examples of the frequency bands allocated for 5G in different countries. Other countries may have different frequency bands assigned for 5G communication, and the list may change as technology evolves and new spectrum options become available. The frequency band allocation aims to provide necessary spectrum resources to support increased data capacity and higher data rates for 5G applications [19-23].

United States	United Kingdom	South Korea	China	Japan	Germany
600 MHz (Band n71)	700 MHz (Band n28)	3.5 GHz (Band n78)	2.6 GHz (Band n41)	3.7 GHz (Band n79)	600 MHz (Band n71)
850 MHz (Band n5)	3.4 GHz (Band n78)	28 GHz (Band n257)	3.5 GHz (Band n78)	28 GHz (Band n257)	850 MHz (Band n5)
1900 MHz (Band n2)					
2.5 GHz (Band n41)					
3.5 GHz (Citizens Broadband Radio Service, CBRS - Band n48)					
28 GHz (Band n260)					
39 GHz (Band n261)					

Figure 1.2. Frequency allocation for 5G communication systems in some countries [19-23].

The emergence of new applications like massive machine-type communications, ultra-reliable low latency communications, and the Internet of Things (IoT) are creating demands that exceed the capabilities of 4G networks. 5G aims to enable these new use cases through radical improvements in data rates, capacity, latency, reliability, and connectivity. A key pillar of 5G is enabling machine-to-machine communication for a heterogeneous ecosystem of devices across industries [23]. This lays the foundation for realizing the full potential of IoT and its transformational impact on sectors like consumer electronics, industrial automation, transportation, healthcare and more. Connecting the estimated 50 billion IoT devices by 2030 requires overcoming 4G limitations. Meeting these diverse service requirements calls for an integrated 5G solution spanning from sub-1 GHz frequencies up to millimeter wave bands above 24 GHz. The FR1 band below 6 GHz will provide wide-area coverage and mobility support, while the FR2 mm Wave band will enable high capacity hotspot coverage through 800 MHz+ of spectrum availability. Advanced antenna technologies will be critical, including massive MIMO, 3D beamforming, and large-scale antenna arrays. Massive MIMO uses large antenna arrays for spatial multiplexing, beamforming, and interference reduction to improve range, reliability and multi-user performance. Metamaterials can significantly advance these antenna capabilities by enabling miniaturization and tailoring EM properties beyond natural materials. Metasurfaces allow stacking multiple antenna arrays in a small footprint through thin low-profile designs. Unique metamaterial properties also enable gain enhancement,

radiation pattern shaping, tunable filtering and reconfigurability. Millimeter waves suffer from higher path loss and sensitivity to blockages. However, the multi-Gbps data rates possible with wide bandwidths at mm Wave frequencies like 28 GHz, 37-40 GHz, and 64-71 GHz make them indispensable for 5G. Carrier aggregation across millimeter wave and microwave bands will help realize target 5G peak rates up to 20 Gbps [19, 23]. While Terahertz bands can provide enormous bandwidths on the order of hundreds of GHz, there are technology gaps in generating, transmitting and detecting THz waves that pose adoption challenges. 6G research is focused on overcoming these to exploit THz spectrum above 95 GHz for ultra-high capacity backhaul and short-range links. In summary, meticulous frequency planning and utilization of both microwave and mm Wave spectrum will be imperative for 5G to deliver the promised gigabit experience and transformational applications. The flexibility of 5G's new air interface and advanced antenna technologies will play a key role in making this feasible [24-26].

1.2. Classification of Materials or Medium

The electromagnetic field relies on the characteristics of the materials involved, described by two constitutive parameters: permittivity (ϵ) and permeability (μ) [27-31]. Fig. 1.3. illustrates the classification of materials based on these fundamental characteristics, which play a crucial role in determining their electromagnetic behavior and applications. Based on the values of permittivity and permeability, materials can be categorized into four groups [27-31]:

- a. **Double Positive (DPS) Material:** These materials have both permittivity and permeability greater than zero ($\epsilon > 0, \mu > 0$). Common media like dielectrics belong to this group.
- b. **Epsilon Negative (ENG) Material:** Materials with negative permittivity and positive permeability ($\epsilon < 0, \mu > 0$) fall into this category. Some plasmas exhibit these properties under specific frequency conditions.
- c. **Mu Negative (MNG) Material:** This type of material has positive permittivity and negative permeability ($\epsilon > 0, \mu < 0$). Certain gyroscopic materials demonstrate these characteristics in particular frequency ranges.
- d. **Double Negative (DNG) Material:** Materials classified as double negative have both permittivity and permeability less than zero ($\epsilon < 0, \mu < 0$). It should be noted that although they usually do not exist in nature, these materials can be artificially produced.

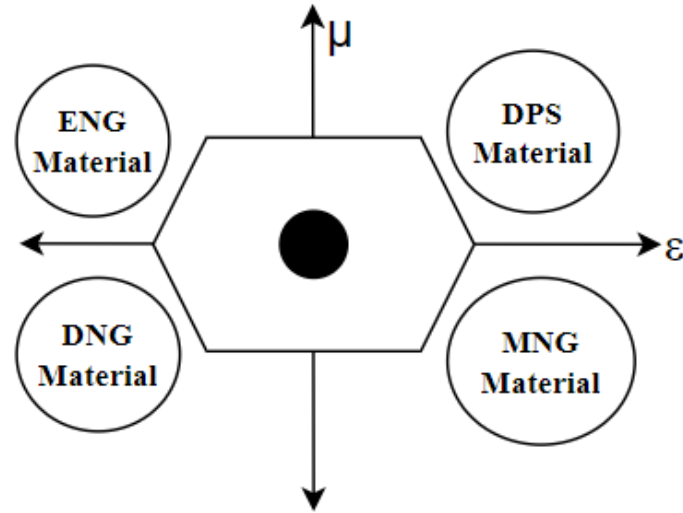


Figure 1.3. Categorization of the materials based on the permittivity and permeability [32]

Dielectric materials or mediums are characterized by their ability to store and transmit electric charges, making them essential components of many electronic devices, such as capacitors and insulators. In a magnetic environment, the effective permeability (μ) is greater than one ($\mu > 1$), while the permittivity (ϵ) is approximately equal to one ($\epsilon \approx 1$). Magnetic environments are capable of channeling and manipulating magnetic fields, and they play a critical role in applications like inductors and magnetic shields. In a conductive environment, the effective permittivity (ϵ) is very large ($\epsilon \gg 1$), and the magnetic permeability (μ) is close to one ($\mu \approx 1$). Such environments exhibit high electrical conductivity, allowing them to efficiently conduct electric currents. Conductive environments are commonly found in metals and are essential in applications like electrical wiring and circuitry. Metamaterials are artificially engineered materials that exhibit unusual and tailored electromagnetic properties not found in nature. In this environment, both the effective permittivity (ϵ) and permeability (μ) can take on negative values ($\epsilon < 0, \mu < 0$) or even simultaneously be negative and positive ($\epsilon < 0, \mu > 0$ or $\epsilon > 0, \mu < 0$). These unique properties enable metamaterials to control and manipulate electromagnetic waves in novel ways, leading to applications like invisibility cloaks, super lenses, and enhanced antennas. It's important to note that metamaterials, which are artificially designed materials with specific electromagnetic properties, can belong to the

ENG, MNG, or DNG categories. These engineered materials have opened up new possibilities for controlling and manipulating electromagnetic waves in various applications.

1.3. Metamaterials

Metamaterials are not found in nature due to their glamorous features. Generally, materials are categorized with respect to the value of constitutive parameters, namely permittivity and permeability. The constitutive parameters of metamaterials are engineered to specified values. Investigation of the metamaterial structures has been dated back to the late 19th century. The first endeavor for metamaterial structure was in 1898 by Jagadish Chandra Bose. He proposed spearheading study for millimeter and microwave applications between 1894 and 1900. He also accomplished experiments to illustrate the polarization effects. Addition to these endeavors, he performed the first man-made twisted structure experiment. These twisted structures were compatible with the artificial chiral structure [33]. Afterwards, Lindell et al. proposed the artificial chiral media which was collection of small wire helices [34]. In 1968, Veselago theoretically examined the double negative material whose permittivity (ϵ) and permeability (μ) had negative values [35]. The aforementioned major quantities define the propagation of electromagnetic waves in any media. In [35], the propagation of the electromagnetic waves in the left-handed media was proposed and the crucial electromagnetic wave laws including Snell's law and Cerenkov effects were explained. It was also concluded in [35] that the media, whose dielectric constant (ϵ_r) and the relative permeability (μ_r) were negative, was left-handed. $\mathbf{E}$, $\mathbf{H}$ and $\mathbf{k}$ (the propagation of the wave) formed the left-handed triplet of the vectors. Pendry et al. focused on the metamaterial structure with metal mesh at ultra-low frequency [36-39]. On the other hand, they also provided microstructures built on non-magnetic conducting sheets, namely Split Ring Resonators (SRR) whose effective magnetic permeability is less than zero [38]. Smith et al. proved the exhibited artificial material with negative permittivity and negative permeability by experiment and simulation techniques. Addition to this challenging feature, they also obtained the negative refractive index in [38]. CST Microwave Studio was used for designing the metamaterial structure and finite integration techniques were applied during simulation process [38]. Shelby et al. verified the negative refractive index at microwave frequency regime experimentally. The proposed structure was made up of 2D array of unit cells of copper line and SRR. The effective refractive index (n_{eff}) was observed with respect to Snell's law. The experimental

results depicted that n was equal to the negative root of ε and μ Negative Index Material (NIM) [40]. Ziolkowski described a passive Lorentz material with matched two-time derivatives, noting that its equivalent permittivity and permeability are reduced compared to those of free space across a wide range of frequencies [41]. After that, Ziolkowski et al. introduced the term of Double Negative Metamaterials (DNG) and deliberated over the wave propagation through numeric and analytic methods [42]. These studies have opened new era of research for scholars on topics such as cloaks, super lens, absorbers, sensors, microwave imaging, energy harvesting and enhancement of antenna structure etc. [43-82].

1.3.1. Metamaterial Inspired Antennas

There are several studies that discuss the use of metamaterials for enhancing antenna performance and electromagnetic wave absorption properties [83-94]. One of them is the study conducted by Feng et al. providing a comprehensive background in analytical theory for parametric interactions in metamaterial multilayer structures with nonlinear electronic and magnetic responses, demonstrating the potential for parametric shielding of electromagnetic fields [95]. Hassan et al. presented a dual-band-notched structure with a wide bandwidth (117.67%) and reduced manufacturing cost due to the selection of FR-4 material [66]. Both proposed antennas showed small size, wider bandwidth, and sharp frequency notch characteristics suitable for IoT applications [72]. Kulkarni et al. depicted a compact multiband metamaterial based microstrip patch antenna for wireless communications in [45]. The simulation process utilized the Agilent Advanced Design System (ADS) software, which includes support for FDTD mode. The chosen metamaterial structure was employed as a superstrate to investigate enhancements in gain and bandwidth. The findings indicated that the antenna, with the metamaterial superstrate, operated effectively across the L, S, and C bands of the electromagnetic spectrum. Additionally, the study proposed reducing the size of the antenna while enhancing its gain, as compared to traditional microstrip patch antennas [45]. The antenna size reduction method was reported by using defected ground plane structure. Lou et al. investigated the high directive planar antenna with one-layer and two-layer metamaterial superstrate for Ku-band applications (13-17 GHz) [88]. In [88], S coupled metamaterial was designed and analyzed in the frequency of Ku-band range. The proposed S coupled metamaterial structure was placed on the superstrate. 5×7 and 6×7 arrays were designed in order to observe the effect of the metamaterial superstrate on the antenna performance. Additionally, refractive indexes of these two proposed structures were retrieved

from scattering parameters. Ansoft HFSS simulation program supported by FEM mode was preferred for analyzing the structures. As a result, the size reduction was not observed. However, the performance of the antenna was improved efficiently [88]. Chen et al. discussed the metamaterial structures such as zero phase shift line, composite left-handed, zero index, mushroom, and high permittivity periodic structures [50]. The proposed metamaterial-based antennas were examined for industrial applications in the frequency ranges from 900 MHz to 60 GHz. The main contribution of [50] was that the proposed metamaterial-based antenna structures have had enormous potentials in forward- looking antenna design and controlling the electromagnetic waves for industrial applications.

1.4. Numerical Methods

Numerical methods play a crucial role in antenna design and analysis due to several important reasons [96-102]:

- i. **Complex Geometry:** Antennas can have intricate geometries that cannot be easily solved analytically. Numerical methods, such as Finite Element Method (FEM) or Method of Moments (MoM), can handle these complex geometries and accurately model the antenna's behavior [96, 100].
- ii. **Material Properties:** Antennas are often made from materials with varying electromagnetic properties. Numerical methods allow for the inclusion of material properties in the simulations, providing a more realistic representation of the antenna's performance [101].
- iii. **Broad Frequency Range:** Antenna behavior needs to be analyzed over a wide frequency range. Numerical methods, like Finite Difference Time Domain (FDTD) and Frequency Domain methods, can handle broadband simulations and assess the antenna's characteristics over a wide spectrum [97,102].
- iv. **Multiphysics Simulations:** Antennas can interact with other physical phenomena, such as thermal, structural, or fluid dynamics effects. Numerical methods in multi-physics simulation software enable engineers to analyze these coupled effects, providing a comprehensive understanding of the antenna's performance [97, 102].
- v. **Parametric Studies:** Numerical methods allow for efficient parametric studies, where engineers can explore different antenna configurations, dimensions, and materials quickly and systematically to optimize the design [98, 102].

- vi. **Antenna Arrays and Complex Structures:** For arrays and larger structures, numerical methods are essential for studying mutual coupling effects and the interaction between individual antenna elements [98, 102].
- vii. **Time-Domain Analysis:** Numerical methods that work in the time domain, such as FDTD, enable engineers to analyze transient effects, time-varying signals, and antenna responses to pulsed excitation [97].
- viii. **Inhomogeneous Media:** Some antennas operate in heterogeneous environments with varying material properties. Numerical methods can accurately handle these inhomogeneous media and predict antenna performance accordingly [99, 102].
- ix. **Validation and Verification:** Numerical simulations can be compared with experimental data for validation and verification, ensuring the accuracy and reliability of the antenna design before physical fabrication [97, 101].

Overall, numerical methods provide a powerful and versatile toolset for antenna engineers and researchers, enabling them to design, analyze, and optimize antennas with high accuracy, efficiency, and flexibility, ultimately leading to improved antenna performance and functionality in various applications. When designing antennas using simulation programs like CST, HFSS, FEKO, and COMSOL, various numerical methods are employed to solve the electromagnetic field equations and obtain accurate results. Some common numerical methods used in antenna design simulations include [96, 103-110]:

- a) **Finite Element Method (FEM):** FEM is widely used in programs like COMSOL for antenna simulations. It discretizes the geometry into finite elements and solves the electromagnetic field equations within each element to approximate the overall behavior of the antenna [103].
- b) **Finite Difference Time Domain (FDTD):** FDTD is a widely used method for time-domain simulations. It discretizes both time and space into finite differences and iteratively updates the electromagnetic fields over time [97,102].
- c) **Method of Moments (MoM):** The MoM is often employed in programs like FEKO. It represents the antenna geometry as a set of unknown currents or charges on its surface and solves integral equations to determine these unknowns [96,109, 110].
- d) **Finite Element Method-Boundary Integral (FEM-BI):** This method combines the FEM for the antenna structure and the BI method for the surrounding space. It is efficient for radiation and scattering simulations [96].

- e) **High-Frequency Structure Simulator (HFSS):** HFSS uses various techniques, including finite element methods, finite element-boundary integral (FEBI), and integral equation solvers, to analyze antenna performance at high frequencies [96].
- f) **Method of Moments in Time Domain (MoM-TD):** This method extends the MoM to time-domain simulations and is well-suited for broadband antennas and transient analysis [96, 109, 110].
- g) **Multilevel Fast Multipole Method (MLFMM):** MLFMM is used in programs like FEKO for efficiently solving large and complex antenna models by approximating interactions between distant parts of the structure [96].
- h) **Shooting and Bouncing Ray (SBR):** SBR is often used for analyzing radiation patterns and scattering characteristics of large and electrically large structures.
- i) **Physical Optics (PO):** PO is particularly useful for analyzing the radiation patterns of metallic antennas and scattering from conducting surfaces [104-107].

These numerical methods enable engineers and researchers to model, simulate, and optimize antenna designs accurately and efficiently, leading to improved antenna performance and functionality. Computational electromagnetic solver programs are advanced software tools used for designing and analyzing antennas. These programs employ numerical methods to solve the complex electromagnetic field equations that govern the behavior of antennas. One of the primary numerical methods used in these programs is the Finite Element Method (FEM) [96], which discretizes the antenna geometry into small elements and solves the electromagnetic equations within each element. This approach allows for accurate representation of the antenna's electromagnetic behavior, making it suitable for a wide range of antenna designs. Additionally, some programs utilize the Method of Moments (MoM) [96, 109, 110], which represents the antenna as a set of unknown currents on its surface, enabling the calculation of radiation patterns and characteristics. The Finite Difference Time Domain (FDTD) [97] method, commonly found in certain programs, provides time-domain simulations to study transient effects and wideband performance. Other numerical techniques, such as the Boundary Element Method (BEM) and Multilevel Fast Multipole Method (MLFMM), are often employed for radiation and scattering analysis, as well as efficient modeling of large and electrically large structures. These computational electromagnetic solver programs and numerical methods collectively offer engineers and researchers powerful

tools for optimizing antenna performance, evaluating various design configurations, and exploring novel antenna concepts in a virtual environment [96-110].

1.5. Fabrication Methods

The selection of fabrication method plays a crucial role in determining the performance, efficiency, and functionality of the designed antennas. There are some key points emphasizing the importance of fabrication methods for antennas. Different fabrication methods may provide different levels of precision in the design of antennas. High-precision methods yield accurate and appropriate antenna geometries, which are necessary to obtain the desired performance and desired radiation properties. Some antennas, especially those used in advanced applications or with specific requirements, may have complex geometries. The choice of fabrication method should be compatible with the design methodology to ensure that the desired antenna shape and characteristics are obtained successfully. Different fabrication methods are applicable for different materials, such as metals, dielectrics, or composites. The selection of the appropriate method is crucial to achieve compatibility with the desired antenna substrate and conductor materials. The fabrication method should be cost-effective and comply with available resources. Some methods may be more cost-effective for large-scale production, while others are more appropriate for low-volume or custom designs. Fabrication methods differ in their production speed and ease of implementation. Time factor is also very important to ensure the design of antennas on time for fabrication and testing. Some methods offer greater flexibility for rapid fabrication. This is particularly valuable during the initial design stages when multiple iterations may be required to optimize the antenna's performance. For antennas intended for mass production, the fabrication method should be scalable to meet high production volumes efficiently and cost-effectively. Advanced fabrication methods, such as 3D printing or Micro-Electro-Mechanical Systems (MEMS), offer the opportunity to explore innovative antenna designs that were previously impractical or unfeasible. The environmental impact of fabrication methods is also an important consideration. Using environmentally friendly techniques and minimizing material waste can be crucial in sustainable antenna manufacturing. As a result, the choice of fabrication method directly affects the antenna's performance, precision, complexity, cost, and overall practicality. It is essential for antenna designers and researchers to carefully evaluate and select the most suitable fabrication method to achieve their design goals and meet specific application requirements effectively. There are several fabrication methods used for

manufacturing antennas, and the choice of method depends on the type of antenna, the materials involved, and the required accuracy. Some common fabrication methods for antennas include the following [111-135]:

- ❖ **PCB (Printed Circuit Board) Fabrication:** PCB antennas are widely used due to their ease of fabrication and cost-effectiveness. The antenna pattern is designed on a PCB substrate using standard PCB manufacturing processes, including chemical etching or photolithography [111-113].
- ❖ **Microstrip Technology:** Microstrip antennas are commonly fabricated using printed circuit board (PCB) processes or thin-film technologies. Microstrip antennas are relatively easy to manufacture and can be integrated into compact and planar structures [114].
- ❖ **Additive Manufacturing (3D Printing):** 3D printing, also known as additive manufacturing, allows for the direct fabrication of three-dimensional antenna structures. This method is particularly useful for creating customized and complex antenna geometries [115, 116].
- ❖ **Dielectric Substrate Cutting:** Antennas on dielectric substrates can be fabricated using cutting methods such as laser cutting, water jet cutting, or CNC milling. These techniques are suitable for various materials, including plastics and laminates [117-119].
- ❖ **Wire Bending and Welding:** For simple wire antennas like dipoles and monopoles, wire bending and welding techniques are often used. These methods are cost-effective and straightforward [120, 121].
- ❖ **Casting and Molding:** For certain types of antennas, such as horn antennas or parabolic reflectors, casting and molding techniques can be used to fabricate the antenna structures with specific materials [115, 122].
- ❖ **Metallization and Sputtering:** Metallization and sputtering processes are employed to deposit metallic films on substrates, creating conductive patterns for antennas [123-128].
- ❖ **Etching:** Chemical etching is a technique for selectively removing material from a substrate to create antenna patterns. This method is widely used for producing microstrip antennas and other planar structures [129, 130].

- ❖ **Surface Mount Technology (SMT):** For small and compact antennas, surface mount technology is employed to mount components directly onto PCBs [131, 132].
- ❖ **MEMS (Micro-Electro-Mechanical Systems):** MEMS technology can be used to fabricate miniaturized and tunable antennas, leveraging microfabrication techniques [133-135].

2. THEORETICAL FOUNDATIONS AND LITERATURE REVIEW

2.1. Reconfigurable Antennas

Reconfigurable antennas have emerged as a promising solution for adapting to the dynamic requirements of wireless communication systems. These antennas offer the ability to change their operational frequency, radiation pattern, polarization, and other characteristics [136]. This flexibility makes them suitable for a wide range of applications, including cognitive radio systems and MIMO (Multiple-Input Multiple-Output) communication. One example of a reconfigurable antenna is the MIMO/UWB (Ultra-Wideband) antenna proposed by Zhao et al. [136]. This antenna operates in a sensing band from 2 to 6 GHz and has several operating bands within this range. The reconfigurability of the antenna allows it to adapt to different frequency bands within its operating range. This capability is particularly useful in cognitive radio applications, where the antenna needs to sense and adapt to available spectrum resources. The design of reconfigurable antennas often involves the use of various techniques and components. For example, in the case of Zhao's MIMO/UWB antenna, the reconfigurability is achieved using PIN (Positive-Intrinsic-Negative) diodes. These diodes can be controlled to switch between different frequency bands, enabling the antenna to adapt to different communication requirements. The theoretical background of reconfigurable antennas lies in the principles of electromagnetic theory and antenna design. The ability of an antenna to change its operating frequency is based on the concept of resonance. By adjusting the dimensions or properties of the antenna structure, it is possible to tune its resonance frequency. This can be achieved by using reconfigurable elements such as diodes or MEMS switches, which can alter the electrical properties of the antenna. In addition to frequency reconfigurability, reconfigurable antennas can also exhibit pattern reconfigurability. This means that the antenna can change its radiation pattern, allowing for beam steering or beamforming. This is particularly useful in MIMO systems, where multiple antennas are used

to transmit and receive signals in different directions. By adjusting the radiation pattern of the antennas, it is possible to optimize the signal quality and improve the overall system performance. Reconfigurable antennas offer a flexible and adaptable solution for wireless communication systems. Through the use of reconfigurable elements and advanced design techniques, these antennas can dynamically adjust their operating frequency, radiation pattern, and other characteristics. This enables them to meet the changing demands of modern wireless communication systems, such as cognitive radio and MIMO applications.

The antenna reconfigurable characteristic can also be implemented by altering the structure of the antenna, which is called the mechanical reconfiguration method. In addition to mechanical reconfiguration, smart materials can also be used to reconfigure the antenna configuration [137]. Various types of reconfigurable antennas, including radiation pattern reconfigurable antennas, polarization reconfigurable antennas, and a combination of radiation and frequency reconfigurable antennas, have been discussed in previous studies in the literature. Other effective implementation techniques for reconfigurable antennas, including electronic switching and other possible switching techniques, have also been investigated [137]. A pattern reconfigurable antenna with multi-beam reconfiguration for satellite communication has been reported in [138]. In 1999, a reconfigurable leaky patch antenna using a PIN diode was presented. Since then, microstrip antennas have been widely used as a platform for designing reconfigurable antennas [138]. Discrete-frequency reconfigurability in antennas can be achieved using various techniques. For example, a single PIN diode can be used for discrete-frequency reconfigurability [139]. Other techniques include embedding varactor diodes in an inset fed microstrip patch antenna, using conductive fabric and PDMS for continuous-frequency reconfigurability, and using flexible substrates such as paper and denim for discrete-frequency reconfigurability. In a recent work, a reconfigurable inverted F-antenna was printed on a kapton substrate, and vanadium dioxide (VO_2) film was used for frequency reconfigurability [139].

2.1.1. Type of Reconfigurable Antennas

Reconfigurable antennas can be classified based on their ability to dynamically adjust operational properties such as frequency, radiation pattern, polarization, or a combination of these factors. These antennas can modify one or more parameters, including frequency, bandwidth, radiation pattern, and polarization [140-149].

Frequency reconfigurable antennas utilize electrical or mechanical mechanisms to alter their resonant frequency. Electrical methods involve using RF switches or varactor diodes for discrete or continuous tuning, respectively. On the other hand, mechanical mechanisms use tunable materials like liquid crystals or metasurfaces to change the antenna's impedance loading [144, 150, 151].

Pattern reconfigurable antennas intentionally modify their radiation pattern by incorporating movable or rotatable structures such as metasurfaces. They may also utilize switchable reactively loaded capacitive elements to adjust the spherical distribution of the radiation pattern [144,150-153].

Polarization reconfigurable antennas switch between different polarizations, such as linear, left-hand circular, and right-hand circular, using multi-mode structures or metasurfaces. This capability is vital for reducing polarization mismatch and losses in portable devices [144,150-153].

Hybrid reconfigurable antennas can simultaneously tune several parameters like frequency, radiation pattern, and polarization independently, often via a parasitic pixel layer. This type of antenna can reconfigure the operating frequency and radiation pattern simultaneously or independently [150-157].

Reconfigurable antennas play an increasingly significant role in modern wireless communication systems due to their adaptability to changing environmental conditions and user needs [141, 144, 145, 152].

Reconfigurable antennas offer the flexibility to change various operating parameters, and their advantages and limitations depend on the specific application and implementation. Each reconfigurable antenna structure can have different designs and configurations tailored to the specific requirements of the application [158]. One example of a reconfigurable antenna is the slot-based CubeSat antenna presented by Hussain et al.in [159]. This antenna is designed for CubeSat applications in the ultra-high frequency (UHF) band and utilizes a frequency reconfigurable (FR) slot-based design integrated on a Rogers RO4350 substrate. The antenna can cover a frequency range of 300-450 MHz [159]. Another example is the frequency reconfigurable planar bow-tie antenna integrated with PIN and varactor diodes and parasitic elements, as proposed by Mariem and Ali [160]. This antenna can switch between six different operating frequency bands using five RF PIN diodes. The simulated results show a

return loss of less than -10 dB and a gain varied between 0.5 and 3.5 dB [160]. In addition to frequency reconfigurability, there are also antennas that offer pattern reconfigurability. Ai-Yasir et al. proposed a pattern reconfigurable circular disk antenna using two PIN diodes for WiMAX/Wi-Fi applications [161]. The antenna utilizes a slot ring and has a reconfigurable radiation pattern. Return losses, peak gains, and reconfigurable radiation patterns are reported for WiMAX/Wi-Fi applications [161]. These examples demonstrate the diversity of reconfigurable antennas and their capabilities in terms of frequency, radiation pattern, and polarization reconfigurability. The specific advantages and limitations of each design depend on the application requirements and the implementation details.

Reconfigurable antennas can be engineered to modify one or more of their operational parameters, such as frequency, bandwidth, radiation pattern, and polarization. These variations can be achieved through different means:

1. **Frequency and bandwidth:** By adjusting their electrical or mechanical properties, reconfigurable antennas can change their resonant frequency and bandwidth. This enables them to operate over various frequency bands and tailor their bandwidth to meet specific signal requirements [162].
2. **Frequency and radiation pattern:** Certain reconfigurable antennas can modify their radiation pattern by altering their physical structure or electrical properties. This adaptability allows them to excel in different signal environments and enhance signal quality [163].
3. **Frequency and polarization:** Reconfigurable antennas can also switch between various polarizations, such as linear, circular, or elliptical. This feature is significant for reducing polarization mismatch and improving signal reception in varying environmental conditions [164].
4. **Radiation pattern and polarization:** Some reconfigurable antennas can simultaneously adjust their radiation pattern and polarization. This capability enables them to effectively adapt to changing signal environments and enhance overall signal quality [163].
5. **Frequency, radiation pattern, and polarization:** Hybrid reconfigurable antennas offer the ability to independently adjust multiple operating parameters, including frequency, radiation pattern, and polarization. This high degree of flexibility allows them to adapt to varying signal conditions and optimize overall performance [163].

The designs and configurations of these antennas can vary based on specific applications and requirements, as presented in Table 2.1. It is important to recognize that these are general characteristics, and the specific advantages and limitations of each reconfigurable antenna structure can vary depending on the application and implementation.

Table 2.1. Comprehensive analysis of the reconfigurable antenna parameters [140-164]

Antenna Structure	Operating Parameters	Mechanism	Advantages	Limitations
Frequency Reconfigurable Antennas	Frequency and Bandwidth	Electrical or Mechanical Tuning	Simple design, Wide frequency coverage, Fast tuning speed	Limited tuning range, High loss in some tuning mechanisms
Pattern Reconfigurable Antennas	Radiation Pattern	Movable or Rotatable Structure, Switchable Capacitive Elements	High radiation efficiency, Wide-angle scanning, Low profile	Limited bandwidth, Narrow beamwidth
Polarization Reconfigurable Antennas	Polarization	Multi-Mode Structure, Metasurface	Low complexity, Reduced polarization mismatch, Compatible with existing communication standards	Limited bandwidth, High cross-polarization levels
Hybrid Reconfigurable Antennas	Frequency, Radiation Pattern, and Polarization	Multiple Radiating Elements, Parasitic Pixel Layer	High flexibility, Wide operating range, Simultaneous tuning of multiple parameters	Complex design, High cost, High power consumption

2.1.2. Group of Antenna Parameters

A reconfigurable antenna can provide the functionality of multiple single-purpose antennas, offering savings in cost, weight, volume, and maintenance expenses. Key parameters that guide antenna development are defined below. Table 2.2 provides a comprehensive overview of the different antenna parameters along with each corresponding description. By addressing these challenges and optimizing the design, reconfigurable antennas can play a crucial role in enabling flexible and efficient wireless communication systems [157].

Table 2.2. Summary of antenna parameter groups [157]

Parameter Group	Examples of Parameters	Description
Physical	Length, width, height, surface area, volume	Describes the physical properties of the antenna structure.
Transition	Input impedance, return loss, reflection coefficient	Describes the performance of the antenna at the interface between the antenna and the feedline or transmission line.
Circuit	Resonant frequency, bandwidth, gain, directivity, radiation pattern	Describes the performance of the antenna as a part of an electrical circuit.
Space	Efficiency, polarization, cross-polarization discrimination	Describes the performance of the antenna in its intended operating environment.

2.1.3. Configurability Mechanisms of Reconfigurable Antennas

The reconfiguration technique depends on the desired adjustable property. There are four major approaches: electrical, optical, mechanical, and material-based. Electrical reconfiguration involves switching components like PIN diodes, MEMS switches, and varactors to alter antenna characteristics [137, 140, 142, 144, 145, 150, 156, 165]. Optical reconfiguration uses photoconductive switches and LEDs to modify properties via light. Mechanical reconfiguration relies on physical motion to reshape the antenna. Material reconfiguration exploits tunable dielectrics, ferrites, liquid crystals, and metamaterials to change electromagnetic properties. Figure 2.1 summarizes these reconfiguration techniques visually. The appropriate technique is chosen based on the target application and reconfigurable traits needed as represented in Table 2.3. A reconfigurable antenna leverages these techniques to deliver multi-antenna functionality from a single compact system.

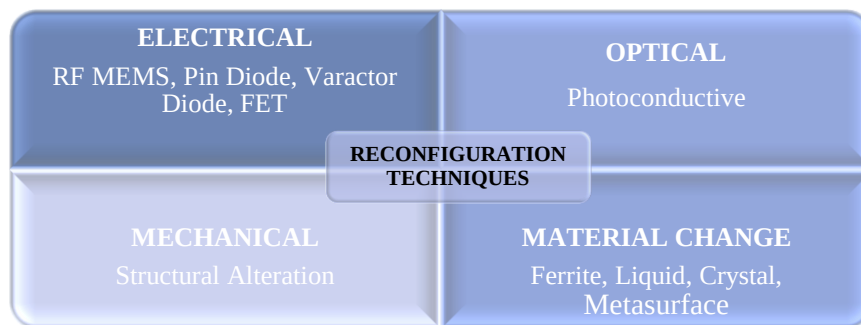


Figure 2.1. Classification of reconfiguration techniques

Table 2.3. Reconfigurable Antenna: Mechanism, description, advantages, disadvantages

Reconfigurability Mechanism	Description	Advantages	Disadvantages
Mechanical Reconfiguration	Changing the physical shape of the antenna to alter its radiation pattern or frequency response	Low cost, can be done with simple mechanisms, high performance	Limited range of reconfigurability, may introduce mechanical wear and tear, may require additional space or weight
Electrical Reconfiguration	Changing the electrical properties of the antenna through electronic components or switching elements	High flexibility, precise control over radiation pattern and frequency response, no mechanical wear and tear	More complex to implement, may introduce additional circuitry and power consumption, limited reconfiguration range
Material Reconfiguration	Changing the dielectric or magnetic properties of the antenna through material changes or chemical processes	High reconfigurability range, can be done with simple mechanisms or chemical processes, low power consumption	Limited performance and durability, may introduce additional material costs, limited range of reconfigurability
Software Reconfiguration	Changing the software that controls the antenna's functionality and radiation pattern	High flexibility, can be done remotely, no additional hardware needed	Limited by the capabilities of the hardware, may require high computing power, may introduce security risks

2.2. Electrically Controlled Reconfigurable Mechanism

Electronically controlled antennas have garnered substantial interest recently due to their dynamic capability to alter operational attributes like frequency, radiation pattern, and polarization. These antennas offer versatility, rendering them apt for diverse wireless communication systems. This literature review delves into various facets of electronically reconfigurable antennas and examines the techniques employed in their realization. A pivotal element in electronically reconfigurable antennas is the utilization of switching methods. Parchin et al. conducted an analysis of switching techniques for such antennas, furnishing an overview of distinct approaches for achieving reconfigurability [137]. The authors explored varied reconfigurable antenna types encompassing radiation pattern, polarization, and radiation-frequencies combinations. These techniques involve manipulating electronic, mechanical, physical, or optical switches to facilitate dynamic tuning of antenna properties. Of the diverse implementation techniques, electronic switches are preminent due to their

efficiency, dependability, and seamless integration with microwave circuitry. These switches find utility in numerous communication systems like satellite communication, multiple-input multiple-output (MIMO) setups, mobile terminals, and cognitive radio communication. Li et al. introduced a polarization-reconfigurable circularly polarized planar antenna utilizing a switchable polarizer [166]. The design harnessed electronic switches to alternate between distinct polarization states, thereby enabling circular polarization reconfiguration. Beyond electronic switches, alternative methods have been explored for reconfigurable antennas. Mechanical reconfiguration involves modifying antenna structure to achieve adaptability. Smart materials are also leveraged to enact reconfigurability by manipulating their properties. Additionally, optical reconfiguration techniques employing photoconductive switching elements have been investigated. Practical instances of electronically reconfigurable antenna implementation have been showcased in various studies. Zhang et al. devised a 1-bit electronically reconfigurable reflect array antenna in the X-band [167]. The antenna integrated a field programmable gate array (FPGA)-based beam control system to effect electronically controlled beam scanning. The prototype exhibited commendable beam-scanning radiation performance, elevated gain, and aperture efficiency.

In summary, electronically reconfigurable antennas furnish adaptability and versatility in wireless communication systems. Their ability to dynamically alter characteristics like frequency, radiation pattern, and polarization is facilitated by diverse switching techniques. Notably, electronic switches are prevalent due to their efficiency and integration ease. Other methods, such as mechanical reconfiguration and smart material application, have also been explored. Practical demonstrations of electronically reconfigurable antennas underline their potential to enhance wireless communication systems. Table 2.4 summarizes common components for electrical control: diodes, transistors, MEMS switches, varactors, and tunable capacitors. Each component facilitates reconfigurable antennas with dynamic, electrically-driven radiation characteristics [137, 168].

Table 2.4. Common components used in electrically controlled reconfigurable antennas

Component	Description	Advantages	Disadvantages
PIN Diode	A type of diode that can be switched between two states using a voltage signal	Low insertion loss, high isolation between states, can operate at high frequencies	Limited reconfigurability range, requires high voltage to switch
MEMS Switch	A micro-electromechanical system switch that can be controlled electronically to switch between different states	Low power consumption, high isolation between states, can be designed for high frequency operation	Limited switching speed, may introduce mechanical wear and tear, may require specialized fabrication techniques
Varactor	A type of tunable capacitor that can be used to shift the resonant frequency of the antenna	Low cost, can be easily integrated into existing designs, wide range of reconfigurability	Limited power handling capacity, limited Q-factor
Tunable Capacitor	A type of capacitor that can be adjusted to tune the resonant frequency of the antenna	High precision tuning, low insertion loss, can be designed for high frequency operation	Limited range of reconfigurability, requires specialized fabrication techniques
RF Relay	An electromagnetic switch that can be used to switch between different antenna elements or configurations	High isolation between states, low insertion loss, can operate at high frequencies	Limited switching speed, may introduce additional complexity and power consumption
Phase Shifter	An electronic component that can be used to adjust the phase of the signal in the antenna	High precision control over radiation pattern, can be used for beamforming and direction finding	Limited range of reconfigurability, may introduce additional complexity and power consumption

Some theoretical information about PIN diodes and RF switches in the context of microwave, antenna, and electronics engineering:

2.2.1. PIN Diodes

A PIN diode is a type of diode that can be used as an electronic switch or attenuator in microwave and RF circuits. The PIN in the name stands for P-type, Intrinsic, and N-type, referring to the three layers of the diode. The intrinsic layer is a lightly doped semiconductor material that acts as the variable resistor of the diode in virtue of forward biased [169]. Figure 2.2 represents the circuit symbol and its layers of PIN diode.

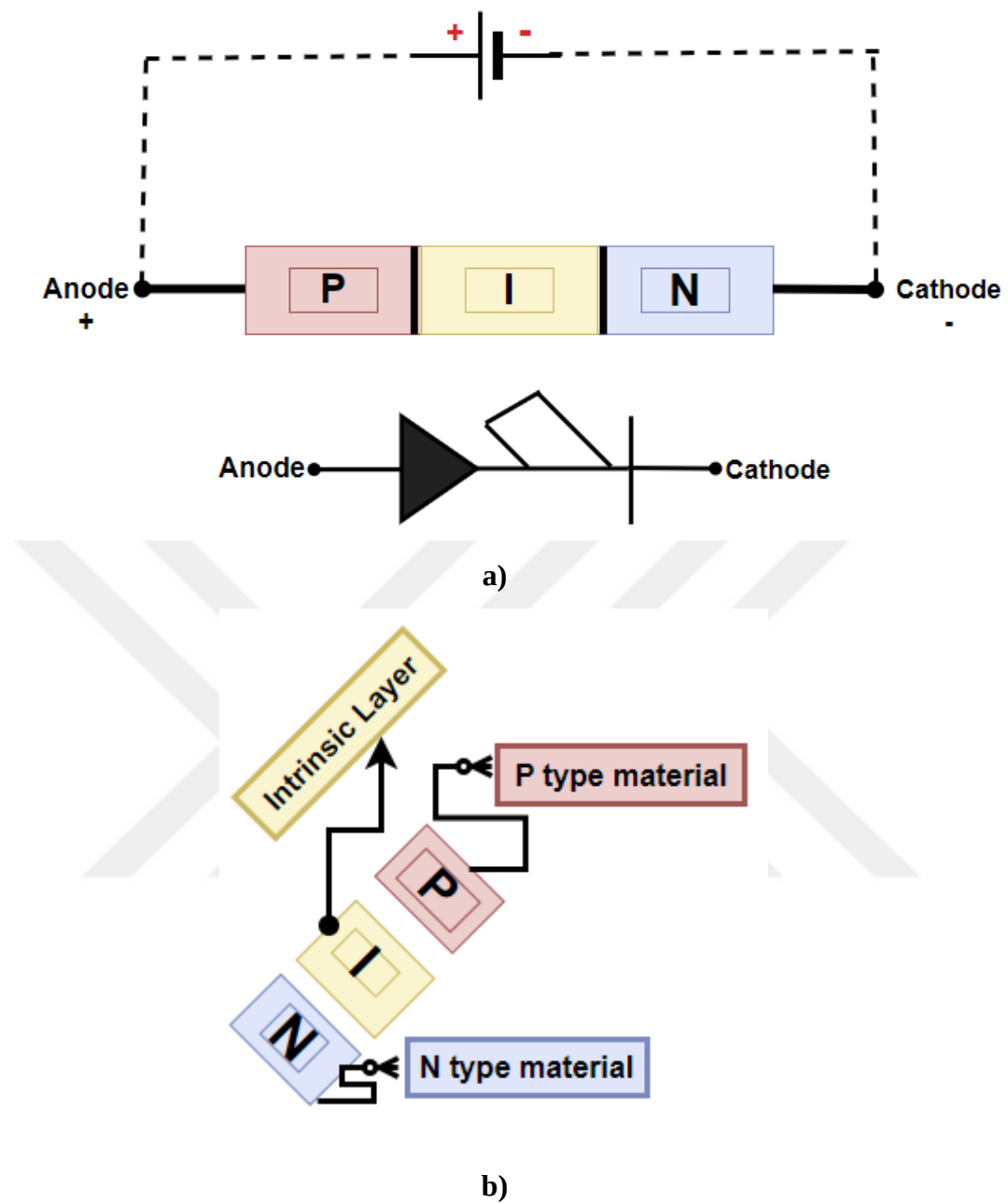


Figure 2.2. a) Circuit symbol and b) layers of PIN diode [169]

When a reverse bias voltage is applied to the diode, the depletion region widens, reducing the resistance of the intrinsic layer and allowing current to flow through the diode. PIN diodes can operate at high frequencies, up to several GHz, making them useful in microwave and RF circuits. PIN diodes can be used as switches by switching the bias voltage between the on and off states, which can be used to control the path of RF signals in a circuit [144, 145, 156, 169-175]. In antennas, PIN diodes can be used to switch between different antenna elements or configurations, allowing the antenna to adapt to changing requirements or conditions. PIN

diodes are commonly used in applications such as mobile communication systems, radar systems, and wireless sensor networks [143, 145, 150, 153, 157, 161, 170, 171, 175, 176-178].

The current-voltage (I-V) characteristic of a PIN diode can be described using the Shockley diode equation [169, 179]:

$$I = I_s \times e^{(qV/(nkT)) - 1} \quad (2.1)$$

where I is the diode current, I_s is the saturation current, q is the electron charge, V is the voltage across the diode, n is the ideality factor (which accounts for non-ideal effects such as recombination), k is Boltzmann's constant, and T is the temperature in Kelvin.

The resistance of a PIN diode in the on state can be approximated using the equation:

$$R_{on} = (2nkT/q) (1/I_s) e^{(qV_{on}/(n kT))} \quad (2.2)$$

where V_{on} is the forward voltage across the diode in the on state.

The capacitance of a PIN diode in the off state can be approximated using the equation:

$$C_{off} = \sqrt{\frac{q\epsilon_r N_d}{2 \times V_{bi}}} \quad (2.3)$$

where ϵ_r is the relative permittivity of the diode material, N_d is the doping concentration, and V_{bi} is the built-in potential of the diode.

The switching time (t_{sw}) of a PIN diode can be estimated using the equation:

$$t_{sw} = R_{on} \times C_{off} \ln \frac{(V_{on} - V_{off})}{(V_{on} - V_f)} \quad (2.4)$$

where V_{off} is the off-state voltage, and V_f is the forward voltage drop across the diode when conducting.

In antenna design, PIN diodes can be used to switch between different antenna elements or configurations, which can affect the radiation pattern, frequency response, or impedance matching properties of the antenna. PIN diodes can also be used as variable attenuators in RF circuits, where the attenuation level can be controlled by varying the bias voltage across the diode. The performance of PIN diodes in microwave and RF circuits depends on several factors such as the doping concentration, the diode size, the bias voltage, the operating frequency, and the series resistance and capacitance of the diode. In order to optimize the performance of a PIN diode in a given application, it is important to consider its I-V characteristics, capacitance, switching speed, and losses, and to choose the appropriate bias voltage and operating conditions.

The I-V characteristic of BAR64-02V pin diode is paramount importance for the selection criteria to design and analysis any frequency reconfigurable antenna using PIN diode. The I-V characteristic of a PIN diode is a plot of the current (I) through the diode versus the voltage (V) applied across it. The BAR64-02V is a low capacitance PIN diode, which means that it can switch quickly and has a low insertion loss. Its I-V characteristic curve shows that it has a low forward resistance (typically less than 1 ohm) at low forward bias voltage levels, and as the voltage increases, the resistance increases as well. To obtain a frequency reconfigurable antenna using the BAR64-02V PIN diode, the following selection criteria should be considered:

- The diode should be capable of operating at the desired frequency range. The BAR64-02V is a high-speed switching diode that can operate up to 4 GHz, making it suitable for sub-6 GHz applications.
- The diode should have low capacitance and high linearity to minimize insertion loss and distortion in the antenna circuit.
- The diode should have a low series resistance to minimize power loss in the antenna circuit.
- The diode should have a high reverse breakdown voltage to ensure that it can withstand the voltage levels present in the antenna circuit.
- The diode should have a fast-switching speed to enable rapid reconfiguration of the antenna frequency.

By selecting the BAR64-02V PIN diode based on the above criteria, it can be used in a switchable network within the antenna circuit. By applying different voltages to the diode, its capacitance and resistance can be controlled, enabling the antenna to operate at different frequencies.

BAR64-02V is a high-performance PIN diode that is commonly used in frequency reconfigurable antennas for sub-6 GHz applications. However, there are other PIN diodes that can also be used for this purpose. Here are some comparisons of other PIN diodes with BAR64-02V [180-183].

MA4E2054: This is another high-performance PIN diode that can be used in frequency reconfigurable antennas. It has a similar forward voltage (V_f) and capacitance (C_t) to BAR64-02V, but a slightly lower maximum power dissipation (PD) rating. However, it has a faster switching speed (t_{sw}) than BAR64-02V, which can be advantageous in some applications [183].

MA4E1317: This is a low-capacitance PIN diode that can be used in high-frequency applications. It has a lower capacitance (C_t) than BAR64-02V, which can be advantageous in some applications, but also has a higher forward voltage (V_f) and slower switching speed (t_{sw}). Its maximum power dissipation (PD) rating is also lower than that of BAR64-02V [184].

BBY58-02W: This PIN diode is suitable for use in tuner circuits, RF switches, and phase shifters [185].

HSMP-3814: This PIN diode is optimized for high-frequency applications and is suitable for use in high-frequency switches, RF attenuators, and phase shifters [186].

In general, the choice of PIN diode for a frequency reconfigurable antenna will depend on the specific requirements of the application. Factors such as the operating frequency range, power requirements, switching speed, and capacitance will all need to be considered when selecting a PIN diode. The BAR64-02V is a good choice for sub-6 GHz applications, but other PIN diodes may be more suitable for higher-frequency or higher-power applications. The commonly used diodes are given in Table 2.5 as follow:

Table 2.5. Commonly used diodes for RF applications

PIN Diode Model	(V_f) [V]	(V_r)* [V]	(C_t) [pF]	(PD) [mW]	(t_{sw}) [ns]	Specific Applications
BAR-64 02V	1.5	50	0.2	500	10	Frequency reconfigurable antennas for sub-6GHz applications
MA4E2054	1.5	50	0.2	350	5	Frequency reconfigurable antennas, RF switches, attenuators, phase shifters
MA4E1317	2.0	50	0.05	300	20	RF switches, phase shifters, limiter diodes, mixer diodes
BBY58-02W [185]	1.3	50	0.25	250	4	Tuner circuits, RF switches, phase shifters
HSMP-3814 [186]	1.5	50	0.6	1000	2	High-frequency switches, RF attenuators, phase shifters

*V_r: Reverse Voltage

2.2.2. RF Choke Inductor and DC Block Capacitor

The RF choking inductor is another component that is often used in the bias circuitry for PIN diodes in RF applications. The purpose of the RF choking inductor is to isolate the DC bias source from the RF signal path, preventing any DC bias current from flowing through the RF signal path. The RF choking inductor is typically placed in series with the bias resistor and DC bias source, between the PIN diode and the blocking capacitor. The value of the RF choking inductor depends on the specific requirements of the application and the frequency range of operation. For sub-6 GHz applications, the RF choking inductor value is typically in the range of a few nanohenries to a few microhenries. The exact value can be determined through circuit simulations and optimizations or based on the datasheet recommendations of the PIN diode and other components in the circuit [187].

A DC block capacitor, often referred to as a DC blocking capacitor or DC decoupling capacitor, is a crucial component in the design of RF (radio frequency) circuits, including frequency reconfigurable antennas. Its primary function is to block direct current (DC) while allowing alternating current (AC) or RF signals to pass through. In the context of frequency

reconfigurable antennas, these capacitors play a vital role in isolating the DC bias or control voltage from the RF signal path. Frequency reconfigurable antennas typically incorporate tuning mechanisms like varactors or PIN diodes to adjust their resonant frequency. These mechanisms require DC biasing or control voltages, and DC block capacitors are used to separate this DC bias from the RF signal path to prevent interference. DC block capacitors are passive electronic components composed of two conductive plates separated by an insulating dielectric material. Their design is centred on preventing the flow of DC voltage while permitting the passage of AC or RF signals. The critical parameters to consider when working with DC block capacitors include the capacitance value, which determines the capacitor's frequency response and its effectiveness in blocking DC voltage. Capacitance values are usually expressed in microfarads (μF) or picofarads (pF) and should be selected based on the specific needs of the application.

In summary, the RF choking inductor is an important component in the bias circuitry for PIN diodes in RF applications. Its purpose is to isolate the DC bias source from the RF signal path, preventing any DC bias current from flowing through the RF signal path. The value of the RF choking inductor depends on the specific requirements of the application and the frequency range of operation. It's also important to choose DC block capacitors with frequency ranges that align with the desired operating frequencies of the reconfigurable antenna. The voltage rating of the capacitor is crucial, as it should withstand the applied DC bias voltage without breakdown or voltage leakage. Careful consideration is necessary to ensure that the selected capacitor can handle the maximum DC voltage within the circuit.

2.2.3. RF Switches

RF switches are electronic components used to route RF signals between different paths or components in a circuit. They find applications in signal routing, impedance matching, filtering, and other functions in microwave and RF circuits [188]. RF switches can be categorized into different types based on their switching mechanism, including mechanical switches, solid-state switches, and MEMS switches [188]. Mechanical switches use physical mechanisms like relays or toggle switches, while solid-state switches employ electronic components such as PIN diodes or FETs. MEMS switches utilize micro-electromechanical systems for mechanical switching [188]. The performance characteristics of RF switches can

vary depending on the type of switch and the specific application. Some common performance metrics include insertion loss, isolation, switching speed, power handling, and reliability [188]. These metrics determine the efficiency and effectiveness of the switch in its intended application. In the field of antenna design, RF switches play a crucial role in enabling the switching between different antenna elements or configurations [189]. This capability allows antennas to have multiple radiation patterns or frequency responses, enhancing their adaptability and versatility [189]. For example, in reconfigurable reflect array antennas, RF MEMS switches are used to control the phase swing of each element, enabling the antenna to achieve desired beam steering and beam shaping characteristics [189]. This technique offers broadband reconfigurability, linear phase swing, and ease of RF MEMS implementation [189]. RF switches are widely used in various applications, including wireless communication systems, RF instrumentation, and microwave test and measurement equipment [189]. They are significant for efficient and reliable operation of RF circuits and systems.

2.2.4. Single-Pole Double-Throw (SPDT) Switch

SPDT (Single-Pole Double-Throw) switches are commonly used in RF and antenna applications for signal routing and reconfigurability. In the context of RF MEMS switches, SPDT switches have been integrated into multiband antennas to enable sequential activation and deactivation of different antenna parts [190]. This implementation eliminates the need for individual switch DC bias lines, as the electrostatic MEMS switches are directly actuated through the RF signal feed [190]. The reconfigurable antennas fabricated on flexible organic polymer substrates can operate at multiple frequencies while maintaining their radiation characteristics [190]. In the field of RF switches, SPDT switches have also been integrated with bandpass filters to achieve combined functionality [191]. This integration allows for the realization of a compact switch-filter module with desirable performance characteristics. For example, a 1-GHz SPDT hybrid switch with a 1.5-dB insertion loss and 20-dB isolation at the center frequency has been demonstrated [191]. Additionally, a 60-GHz SPDT switch with low insertion loss (<2.5 dB) and high isolation (>27 dB) has been developed, showcasing the compatibility of the switch with the filter function [191]. The design and performance of SPDT switches are crucial in achieving the desired functionality in RF and antenna applications. High isolation between transmitter and receiver is a key requirement to minimize RF power leakage and distortion [192]. The use of switchable SIW (Substrate

Integrated Waveguide) resonators has been explored to enhance the isolation of SPDT switches in millimeter-wave MIMO (Multiple-Input Multiple-Output) transceivers [193]. The proposed SPDT switch design demonstrated an isolation higher than 25 dB within a specific frequency range [193]. Furthermore, the development of SPDT switches extends to advanced technologies such as fully-depleted silicon-on-insulator (FDSOI) CMOS (Complementary Metal-Oxide-Semiconductor) [194]. A 28 GHz broadband SPDT distributed traveling-wave RF switch designed in a 22 nm FDSOI CMOS technology has been presented [194]. This switch covers specific bands of fifth-generation (5G) mobile wireless systems and exhibits compatible performance with other millimeter-wave RF switches [194]. In summary, SPDT switches are widely used in RF and antenna applications for signal routing, reconfigurability, and integration with other components such as filters. They enable the sequential activation of antenna parts, eliminate the need for individual switch DC bias lines, and provide desirable performance characteristics such as low insertion loss, high isolation, and compatibility with specific frequency bands. The design and performance of SPDT switches play a crucial role in achieving efficient and reliable RF and antenna systems.

SPDT switches are also important in designing reconfigurable antennas for sub-6GHz applications. These switches enable the antenna to switch between different operating modes or frequency bands, providing flexibility and adaptability to changing communication requirements. The use of SPDT switches in reconfigurable antennas allows for the selection of different antenna configurations or resonant frequencies, enhancing the antenna's performance and versatility. For example, Dildar et al. developed a frequency reconfigurable monopole antenna with pin diode switches for switching between various operating modes [195]. The antenna exhibited improved radiation gain and efficiency compared to a standard patch antenna array. In the context of millimeter-wave applications, Trzebiatowski et al. proposed a switched beam antenna using an SPDT switch based on PIN diodes [196]. The antenna could electronically switch the main beam in two different directions, providing beam steering capabilities. The integration of the SPDT switch with the antenna structure allowed for dynamic control of the radiation pattern. The use of SPDT switches in reconfigurable antennas extends to various applications, including microwave breast imaging systems, millimeter-wave vehicular communications, and 5G and UWB (Ultra-Wideband) applications [195]. These studies highlight the importance of SPDT switches in achieving frequency reconfigurability and adaptability in antenna designs. The performance of SPDT switches in

reconfigurable antennas is also a subject of research. For instance, Shairi et al. analyzed the performance of different RF switch topologies using discrete PIN diodes [197]. The design of the SPDT switch is crucial to ensure optimal performance and reliability in specific applications. In summary, SPDT switches are essential components in designing reconfigurable antennas for sub-6 GHz applications. They enable the selection of different operating modes or frequency bands, enhancing the antenna's performance and adaptability. The integration of SPDT switches with antenna structures allows for dynamic control of radiation patterns and beam steering capabilities. The design and performance analysis of SPDT switches are critical to achieve efficient and reliable reconfigurable antenna systems.

2.2.5. Lumped Elements

Lumped elements, such as capacitors and inductors, are commonly used in the design of frequency reconfigurable antennas to provide the necessary tuning mechanism. These elements can have several effects on the antenna's performance, including changes in impedance, radiation pattern, bandwidth, and increased complexity. The specific effects will depend on the design and placement of the lumped elements in the antenna structure [198]. A study by Shahmirzadi and Oraizi in 2016 presents a new design of frequency reconfigurable planar coplanar waveguide-fed array antenna for multiband MIMO (multi-input–multi-output) applications [198]. The proposed antenna consists of two identical basic reconfigurable antenna elements, each consisting of two quarter-wavelength resonators. The antenna has a compact size of $48.5 \times 25 \text{ mm}^2$ and achieves more than 16 dB isolation level between its ports for all its various switchable performances. The measured results confirm that the proposed antenna is suitable for modern multiband MIMO applications [198]. Another study by Sato et al. explores a method for reducing electromagnetic coupling between two monopole antennas for MIMO communications without using any lumped element components [199]. The proposed method uses even-odd mode analysis and allows for independent setting of the decoupling condition for each mode. Both decoupling and matching can be designed simultaneously, eliminating the need for lumped element components between antennas [199]. Behdad and Sarabandi in 2006 present a technique for designing dual-band reconfigurable slot antennas [200]. The technique involves loading the slot antenna with two lumped variable capacitors (varactors) placed in proper locations along the slot. By choosing the locations of the varactors appropriately, it is possible to obtain a dual-band antenna with individually controllable resonant frequencies. This allows for fixed frequencies in one band

while the other band can be electronically tuned [200]. Li et al. propose a frequency-reconfigurable bow-tie antenna for Bluetooth, WiMAX, and WLAN applications [201]. The design utilizes a simple biasing circuit that eliminates the need for extra bias lines and avoids distortion of the radiation patterns. The measured results show that the proposed antenna can be tuned to operate in either the 2.2-2.53, 2.97-3.71, or 4.51-6 GHz band with similar radiation patterns [201]. Qiu et al. present a multi-band antenna for metal-rimmed handset terminals [202]. The measured results confirm that the proposed antenna achieves three wide bandwidths, which are consistent with the simulation results. The antenna also exhibits good performance in terms of radiation patterns, efficiencies, and gains [202]. Ren et al. propose two ground radiation antennas with simple feeding structures for mobile applications [203]. The design of the antennas is based on characteristic mode theory. Antenna 1 utilizes a small loop as the feeding structure without any lumped elements [203]. Overall, the use of lumped elements in frequency reconfigurable antennas can have various effects on the antenna's performance, and the specific outcomes depend on the design and placement of these elements. Researchers have proposed different techniques and designs to address the challenges and optimize the performance of reconfigurable antennas in various applications.

Lumped elements, such as capacitors and inductors, are often used in the design of frequency reconfigurable antennas to provide the necessary tuning mechanism. These elements can have several effects on the antenna's performance, including:

- **Changes in antenna impedance:** Adding lumped elements to the antenna design can change the antenna's input impedance, which can affect the antenna's matching to the feedline and overall efficiency. Careful design and optimization of the lumped elements are required to ensure proper impedance matching [201].
- **Changes in antenna radiation pattern:** Lumped elements can also affect the radiation pattern of the antenna, particularly if they are placed near the radiating element. This can lead to changes in the antenna's gain, directivity, and polarization characteristics [204-206].
- **Narrower bandwidth:** In some cases, the use of lumped elements can result in a narrower bandwidth for the antenna, particularly if the elements are used to adjust the antenna's resonant frequency. This can limit the antenna's ability to operate over a wide frequency range [204, 207]. In some cases, the use of lumped elements in frequency reconfigurable antennas can result in a narrower bandwidth for the antenna. This

limitation occurs particularly when the elements are used to adjust the antenna's resonant frequency [207]. The narrow bandwidth can restrict the antenna's ability to operate over a wide frequency range, which may be a disadvantage in applications that require broad frequency coverage [207]. To address this issue, researchers have explored various techniques to improve the bandwidth of frequency reconfigurable antennas. For example, the use of lumped capacitors has been investigated to enhance the bandwidth of circularly polarized printed monopole antennas. By attaching a lumped capacitor in the gap of the antenna, the axial-ratio bandwidth (ARBW) can be significantly improved. Simulation results have shown that the ARBW can increase from 4.1% to 30.7% with the use of a 0.5 pF capacitor [207]. Another approach to overcome the narrow bandwidth limitation is the use of active interior-matching circuits. By replacing the lumped element inductor with negative reactance from a negative impedance converter (NIC), the antenna's bandwidth, radiation gain, and efficiency performance can be significantly improved [204]. This approach acts as an effective interior matching circuit, allowing for a broader bandwidth and improved antenna performance [204]. In summary, while the use of lumped elements in frequency reconfigurable antennas can result in a narrower bandwidth, researchers have explored techniques such as the use of lumped capacitors and active interior-matching circuits to overcome this limitation and improve the antenna's bandwidth performance.

- **Increased complexity:** Incorporating lumped elements into the design of frequency reconfigurable antennas can increase the overall complexity of the antenna, making it more difficult to design, fabricate, and test [208]. The addition of lumped elements introduces additional components and connections, which can complicate the antenna's structure and require careful consideration of the layout and integration of these elements [208]. However, the use of lumped elements is often necessary to achieve the desired frequency reconfigurability and tuning capabilities in the antenna design. Researchers have explored various techniques to mitigate the complexity associated with lumped elements, such as using compact and integrated designs [206], optimizing the placement and integration of the elements [206], and employing equivalent circuit models for analysis and simulation [208]. It is important to strike a balance between the desired performance and the complexity introduced by the lumped elements. Careful design and optimization are required to ensure that the benefits of frequency reconfigurability outweigh the challenges associated with increased complexity [206]. Notwithstanding

these possible outcomes, lumped elements remain a vital element in the creation of frequency reconfigurable antennas. Through meticulous optimization of their positioning and values, it becomes feasible to alleviate any adverse impacts and attain the intended performance attributes for the antenna.

2.2.5.1. Numerical Calculations for Lumped Elements

The series connection of an inductor and capacitor in a frequency reconfigurable antenna affects the S_{11} parameter by altering the antenna's resonance frequency. In a frequency reconfigurable antenna, the resonance frequency can be changed by varying the values of the inductor and capacitor. When the inductor and capacitor are connected in series, they form a resonant LC circuit, and the resonance frequency is given by [209]:

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (2.5)$$

where L is the inductance in Henry, and C is the capacitance in Farads.

The series connection of an inductor and capacitor in a frequency reconfigurable antenna can affect the S_{11} parameter by altering the antenna's resonance frequency [210]. The S_{11} parameter measures the amount of power that is reflected back to the source when a signal is transmitted to the antenna. At the resonance frequency, the S_{11} parameter should ideally be as low as possible, indicating that the antenna is matched to the source impedance and most of the power is transmitted to the antenna. If the resonance frequency is shifted away from the desired frequency, the S_{11} parameter will increase, indicating that more power is being reflected back to the source and less is being transmitted to the antenna. Therefore, the series connection of the inductor and capacitor in a frequency reconfigurable antenna can affect the antenna's resonance frequency and consequently the S_{11} parameter. By adjusting the values of the inductor and capacitor, it is possible to tune the antenna to the desired frequency and achieve a low S_{11} parameter, which is critical for good antenna performance [210].

To tune a frequency reconfigurable antenna to the desired frequency, the values of the inductor and capacitor in the LC circuit must be adjusted. There are several methods that can be used to tune the antenna, including:

- **Variable capacitors and inductors:** These are components that can be adjusted to change their capacitance or inductance, respectively. By using variable capacitors and inductors in the LC circuit, the resonance frequency of the antenna can be adjusted [211].
- **Switched capacitors and inductors:** These are components that can be switched in or out of the LC circuit to change its effective capacitance or inductance. By selectively switching in or out capacitors or inductors of different values, the resonance frequency of the antenna can be adjusted [211].
- **MEMS switches:** These are tiny mechanical switches that can be used to change the capacitance or inductance of the LC circuit. By activating different combinations of MEMS switches, the resonance frequency of the antenna can be adjusted [212].
- **Varactor diodes:** These are semiconductor devices that can be used as variable capacitors. By applying a voltage to a varactor diode, its capacitance can be changed, allowing the resonance frequency of the antenna to be adjusted [212].
- **Digital tuning:** This involves using a microcontroller or digital signal processor (DSP) to control the tuning of the antenna. The microcontroller or DSP can adjust the values of the capacitors and inductors in the LC circuit using any of the above methods, based on feedback from the antenna's performance [211].

In summary, there are several methods to tune a frequency reconfigurable antenna to the desired frequency, and the choice of method will depend on the specific requirements and constraints of the antenna design.

Numerical Calculation for Tuning Capacitor Values

To design the lumped elements for a frequency reconfigurable antenna (FRA) with resonance frequencies of 2.4 GHz, 3.5 GHz, and 5.2 GHz, along with a biasing voltage of 3V, 1000 ohms, and a 68 nH inductor, the values of the tuning components are needed to determine for each resonance frequency. There are some basic steps as given below:

- Determine the values of the inductor and capacitor for each resonance frequency: The resonance frequency of an LC circuit can be calculated using the following equation:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

- We can rearrange this equation to solve for the capacitance:

$$C = \frac{1}{(4\pi)^2 \times L \times f^2}$$

- Using the given values of the biasing voltage (V), resistance (R), and inductor (L), we can calculate the required capacitance (C) for each resonance frequency as follows:

For $f = 2.4$ GHz:

$$C = \frac{1}{(4\pi)^2 \times (2.4 \times 10^9)^2 \times (68 \times 10^{-9})} = 0.397 \text{ pF}$$

For $f = 3.5$ GHz:

$$C = \frac{1}{(4\pi)^2 \times (3.5 \times 10^9)^2 \times (68 \times 10^{-9})} = 0.220 \text{ pF}$$

For $f = 5.2$ GHz:

$$C = \frac{1}{(4\pi)^2 \times (5.2 \times 10^9)^2 \times (68 \times 10^{-9})} = 0.135 \text{ pF}$$

- *Determine the values of the tuning components for each resonance frequency:* The calculated capacitance values are used to determine the values of the tuning components required for each resonance frequency. For example, if varactor diodes are used as the tuning components, the required capacitance can be calculated range and choose varactor diodes with appropriate capacitance values.
- *Design the lumped elements:* The lumped elements for each resonance frequency can be designed based on the chosen tuning components. For example, if varactor diodes are used, the matching network would be designed to connect the varactor diodes to the antenna and the biasing circuit.

In summary, to design the lumped elements for a frequency reconfigurable antenna with resonance frequencies of 2.4 GHz, 3.5 GHz, and 5.2 GHz. To determine the needed capacitance for each frequency, it is necessary to calculate it using the LC resonance equation and then compute the values of the tuning components based on the selected tuning method. The design of the lumped elements generally depends on the specific requirements and constraints of the FRA design.

2.2.5.2. Interpretation of the Lumped Elements

One example of the effects of lumped elements in the biasing circuitry for frequency reconfigurable antennas is the use of varactor diodes for frequency tuning. Varactor diodes are commonly used to provide frequency tuning in frequency reconfigurable antennas, and they require a biasing circuit to control their capacitance. The biasing circuitry for varactor diodes typically includes lumped elements, such as resistors, capacitors, and inductors, which can affect the performance of the antenna in several ways. For example:

- **Change in resonant frequency:** The capacitance of the varactor diode can be tuned by changing the voltage bias applied to it through the biasing circuit. The presence of the lumped elements in the biasing circuit can affect the tuning range and speed of the varactor diode, which can in turn affect the resonant frequency of the antenna.
- **Narrower bandwidth:** The use of varactor diodes in the antenna design can result in a narrower bandwidth for the antenna due to the increased loss associated with the biasing circuit. This can limit the antenna's ability to operate over a wide frequency range.
- **Increase in insertion loss:** The lumped elements in the biasing circuit can introduce additional insertion loss, which can reduce the efficiency and gain of the antenna.
- **Changes in radiation pattern:** The presence of the lumped elements in the biasing circuit can also affect the radiation pattern of the antenna, particularly if they are placed near the radiating element. This can lead to changes in the antenna's gain, directivity, and polarization characteristics.

To mitigate these effects, careful design and optimization of the biasing circuitry is necessary. This may involve selecting the appropriate values for the lumped elements, optimizing their placement in the circuit, and minimizing their impact on the antenna's performance.

2.3. Metamaterial-Inspired Frequency Reconfigurable Antennas

Metamaterial-inspired frequency reconfigurable antennas have become an area of active research due to their ability to adapt to changing operating conditions, making them suitable for use in dynamic communication and sensing environments. In general, frequency reconfigurable antennas are designed to operate over a range of frequencies, and their resonant frequency can be tuned by adjusting the properties of the antenna structure. Alibakhshikenari et al. developed a metamaterial-inspired antenna array for microwave breast

imaging systems [213]. The array operates over the frequency range of 2-12 GHz and exhibits improved radiation gain and efficiency compared to a standard patch antenna array. Coll-Perales et al. proposed a sub-6 GHz assisted MAC for millimeter-wave vehicular communications [214]. The scheduling proposal ensures that the proposed scheduling does not affect the normal operation of vehicular applications relying on sub-6 GHz V2X communications. Sarkar et al. presented a multi-band microstrip-fed slot antenna loaded with a split-ring resonator [215]. The antenna design utilizes sub-wavelength resonators and demonstrates satisfactory gain and radiation patterns in all operating bands. These studies highlight the potential of metamaterial-based antennas for sub-6 GHz applications, including microwave breast imaging systems and millimeter-wave vehicular communications. The use of metamaterials allows for improved antenna performance, frequency reconfigurability, and enhanced electromagnetic wave absorption properties. These advancements contribute to the development of efficient and versatile antennas for various applications in the sub-6 GHz frequency range.

The development of reconfigurable antennas using metamaterials is critical to fully utilize the potential of 5G in the sub-6 GHz frequency range. Metamaterials empower reconfigurable antennas with properties like frequency tuning, radiation pattern control, and polarization flexibility beyond what is possible with conventional antennas. This allows a single reconfigurable metamaterial antenna to adaptively serve multiple 5G frequency bands, beam directions, and polarizations through external control. Reconfigurable antennas will be a key enabler for sub-6 GHz 5G devices and networks to intelligently adapt to dynamic environments and varying requirements, by maximizing spectral efficiency, optimizing link performance, mitigating interference, and supporting advanced beamforming. The integration of reconfigurable antennas with metamaterial structures is therefore essential for unlocking the full capabilities of sub-6 GHz 5G systems and creating truly intelligent antenna systems that go beyond the limitations of fixed antennas.

3. FREQUENCY AGILITY: DEVELOPING A RECONFIGURABLE ANTENNA FOR MULTIPLE ACCESS NETWORKS

In this chapter, a new frequency reconfigurable antenna is created to enable its smooth integration into various access networks within a single device. The antenna utilizes two distinct switches that provide frequency agility. Furthermore, a DC biasing network is utilized for the elimination of the signal distortion between DC signal and RF signal. PIN diodes are defined as discrete port to process the numerical analysis through the touchstone files, which comprise scattering parameters data.

Moreover, the study presents a method to remotely control and monitor the frequency reconfigurable antenna using IoT-based technology. Numerical and experiment outcomes demonstrate the antenna's performance parameters, underscoring the significance of this research. A comparison with previous studies in the literature illustrates the antenna's frequency reconfigurability in the sub-6 GHz range.

The findings indicate that the proposed antenna can cover a wide range of mobile and wireless communication systems, including 5G NR n1 band (2.09 GHz), Wi-Fi (IEEE 802.11a/n/ac), Bluetooth (5 GHz), WLAN (5.3 GHz), Commercial Wi-Fi (5.3 GHz), Long Term Evolution (LTE) (2.15 GHz), 3G (UMTS), and ISM band (5 GHz). Lastly, the study discusses the implications and potential future developments of the proposed antenna.

3.1. Antenna Design

3.1.1. Simulation Design

Given the heightened demand for advanced wireless systems, the development of novel antenna designs assumes a critical role in facilitating the operation of multiple frequency bands. Throughout the design phase, a pivotal consideration revolves around crafting innovative antenna structures that fit seamlessly within a compact wireless device. Consequently, this study dedicates significant attention to this geometric limitation as a primary objective. A novel antenna geometry is established, featuring an inner spiral resonator interconnected with an outer split-ring radiator. The strategic integration of resonators and split-ring radiators is aimed at achieving a reduction in the overall antenna

The determination of the feed line width (W_f) in the proposed antenna design is grounded in standard transmission line theory, as indicated in references [221, 222]. This well-established theory furnishes a robust framework for establishing appropriate dimensions of transmission lines, ensuring efficient signal propagation within the antenna structure. By adhering to the principles and guidelines originating from this theory, designers can attain optimal performance and impedance matching, rendering it an indispensable reference throughout the developmental process. Furthermore, the effective dielectric constant (ϵ_{eff}) is evaluated using Equation (3.1) [222], which correlates the feed line width (W) with the substrate height (h). This calculation offers insights into the effective dielectric environment encompassing the feed line, thereby influencing the overall antenna performance.

To achieve a $50\ \Omega$ impedance match, the characteristic impedance (Z_o) of the feed line is validated using Equation (3.2) [222]. Impedance matching stands pivotal in curtailing signal reflections and maximizing power transfer between the antenna and the connected system.

Subsequently, the wavelengths (λ) corresponding to the lowest and highest frequencies are ascertained via Equation (3.3) [221- 223]. These wavelengths furnish invaluable data for evaluating the antenna's resonant behavior at specific frequencies.

By establishing the wavelengths, the effective resonant lengths (L_{on-on} and $L_{off-off}$) for distinct antenna states are computed, set at $\lambda/4$ to achieve the targeted resonance. These resonant lengths wield substantial influence over the antenna's efficiency and radiation characteristics at the prescribed frequencies.

The electrical lengths for varying states are deduced by computing $\lambda_1 = 57\text{ mm}$ and $\lambda_2 = 125\text{ mm}$ for the upper and lower frequencies, respectively, employing Equation (3.3). These electrical lengths denote the physical dimensions of the antenna elements requisite to attain resonance at their respective frequencies.

Post the acquisition of wavelengths and effective resonant lengths for each frequency band (5.2 GHz and 2.4 GHz), a parametric sweep is undertaken to optimize the values of the other designated dimensions illustrated in Figure 3.1. This iterative process entails the adjustment of diverse antenna parameters, including element lengths, spacing, and angles, in pursuit of identifying the optimal configuration that aligns with desired performance criteria such as gain, radiation pattern, and impedance matching.

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left\{ \left(1 + 12 \frac{w_f}{h} \right)^{-0.5} \right\} \quad \text{where } \left(\frac{w}{h} > 1 \right) \quad 3.1$$

$$Z_o = \frac{120\pi}{\sqrt{\epsilon_{eff} \left[\frac{w}{h} + 1.393 + \frac{2}{3} \ln \left(\frac{w}{h} + 1.44 \right) \right]}} \quad 3.2$$

$$L_R = \frac{c_o}{4 f_c \sqrt{\epsilon_{eff}}} \quad 3.3$$

3.1.2. Parametric Analysis and Equivalent Circuit

3.1.2.1. Parametric Analysis

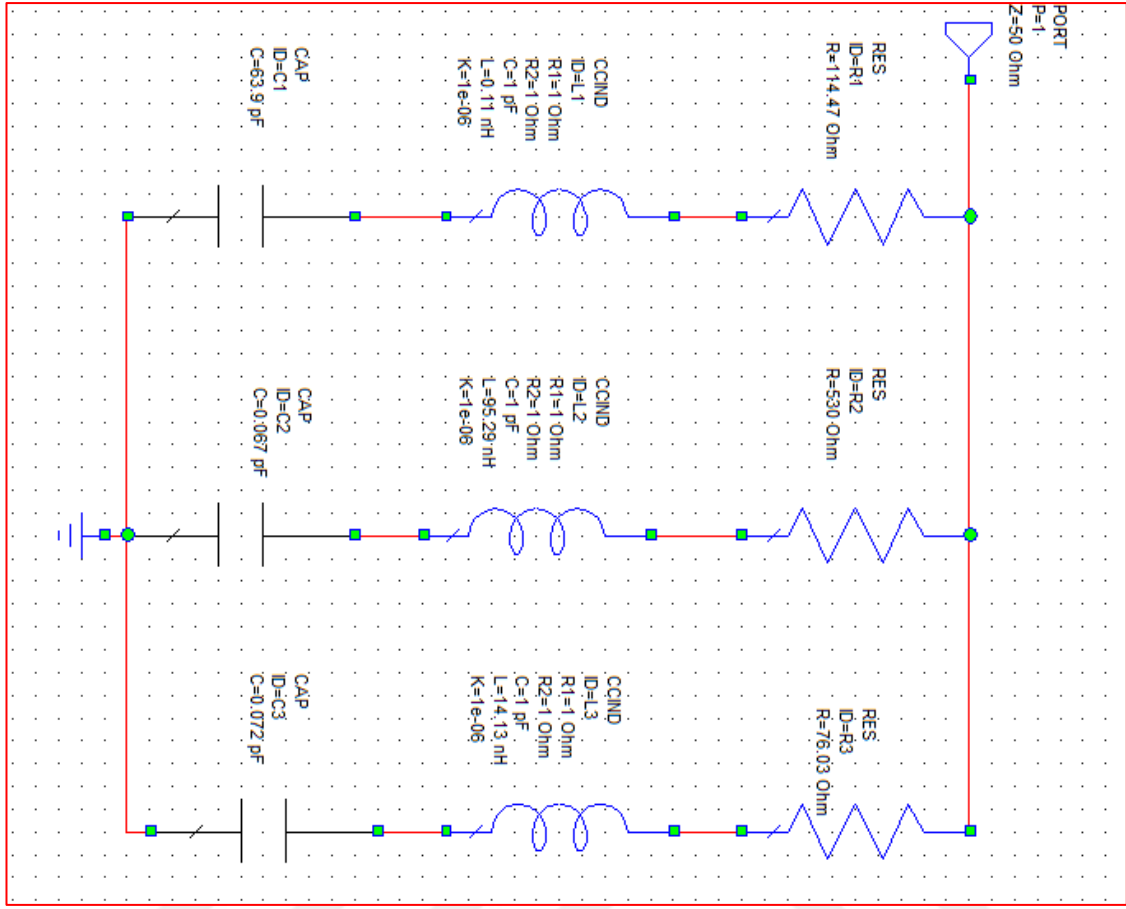
When developing the proposed antenna structure, several critical design parameters, such as the dielectric constant, effective dielectric constant, wavelength, and characteristic impedance, are carefully considered. To address potential issues and optimize performance, parametric analysis and theoretical calculations are conducted. The effective dielectric constant is determined using equations from Bahl and Trivedi's study [224], which rely on the dielectric height and transmission line width. These equations highlight the significance of the effective dielectric constant, dielectric height, and transmission line width for the antenna design. By employing Equations 3.1-3.3, initial fundamental physical parameters are calculated to define the operating frequency ranges for different antenna states. Subsequently, the geometrical parameters labeled in Figure 3.1a are analyzed through calculations and parametric analysis. The reflection coefficient is assessed for each set of parameter values to evaluate and compare the antenna's performance. The ultimate goal is to find the combination of parameters that achieves optimal antenna performance, and the optimized values are presented in Table 3.1. The iterative process of calculations and parametric analysis ensures that the proposed antenna structure meets the desired performance requirements and operates effectively across different frequency bands.

Table 3.1. Labelled Antenna Physical Parameters

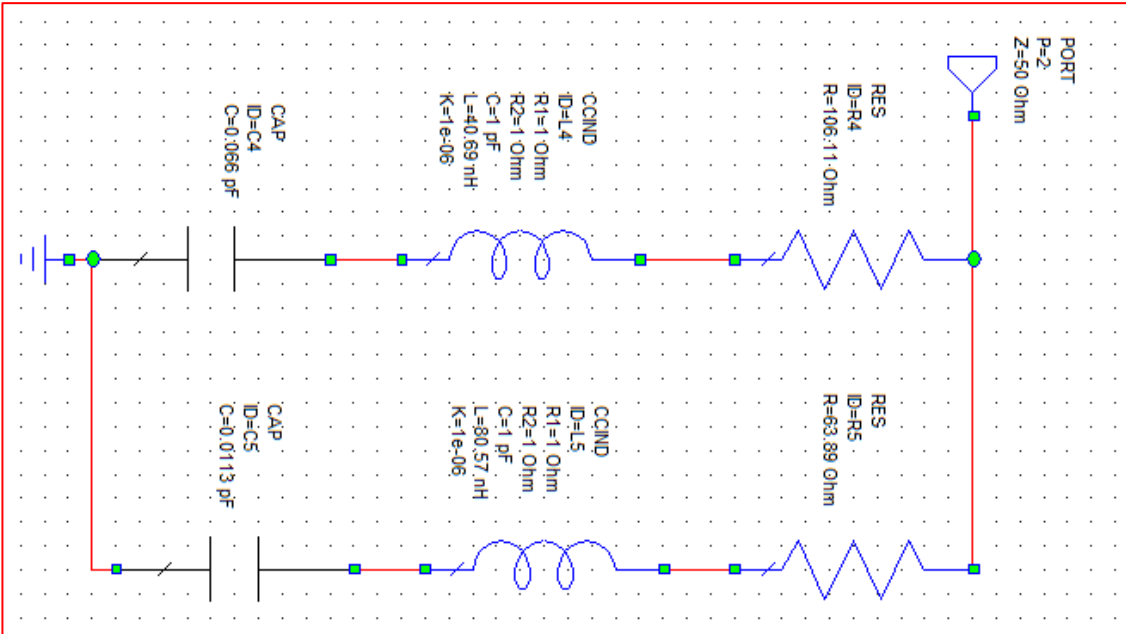
Dimension Label	Unit (mm)
W_s	16
W_{i1}	10
W_{i2}	8
W_o	14
g	1
L_s	22
L_{i1}	8
L_f	9
L_{i2}	6
W_f	3
L_{i3}	3.5
t_m	1
L_o	12
L_g	4

3.1.2.2. Equivalent Circuit

An equivalent circuit model is commonly occupied to tackle the mismatch of the impedance for a reconfigurable antenna, whose common feed line is existed. This model provides an effective approach to address the impedance mismatch by introducing lumped elements for different parts of the antenna. In this study, a detailed equivalent circuit is utilized for both ON-ON and OFF-OFF states, as shown in Figure 3.2. Each individual circuit component is computed individually to match the corresponding resonance condition. The precise values for each element are determined and subsequently integrated into the proposed antenna's equivalent circuit, as shown in Figure 3.2.



a)



b)

Figure 3.2. Equivalent representation of the suggested antenna configuration in (a) ON-ON and (b) OFF-OFF states.

Utilizing the equivalent circuit models provided, Figure 3.3 illustrates the analysis and comparison of the antenna design's reflection coefficient employing two distinct software tools: CST and Advanced Design System (ADS). Through the comparison of reflection coefficients derived from these software tools, the antenna design's performance is corroborated, substantiating its efficacy across the equivalent circuit models for both the ON-ON and OFF-OFF states.

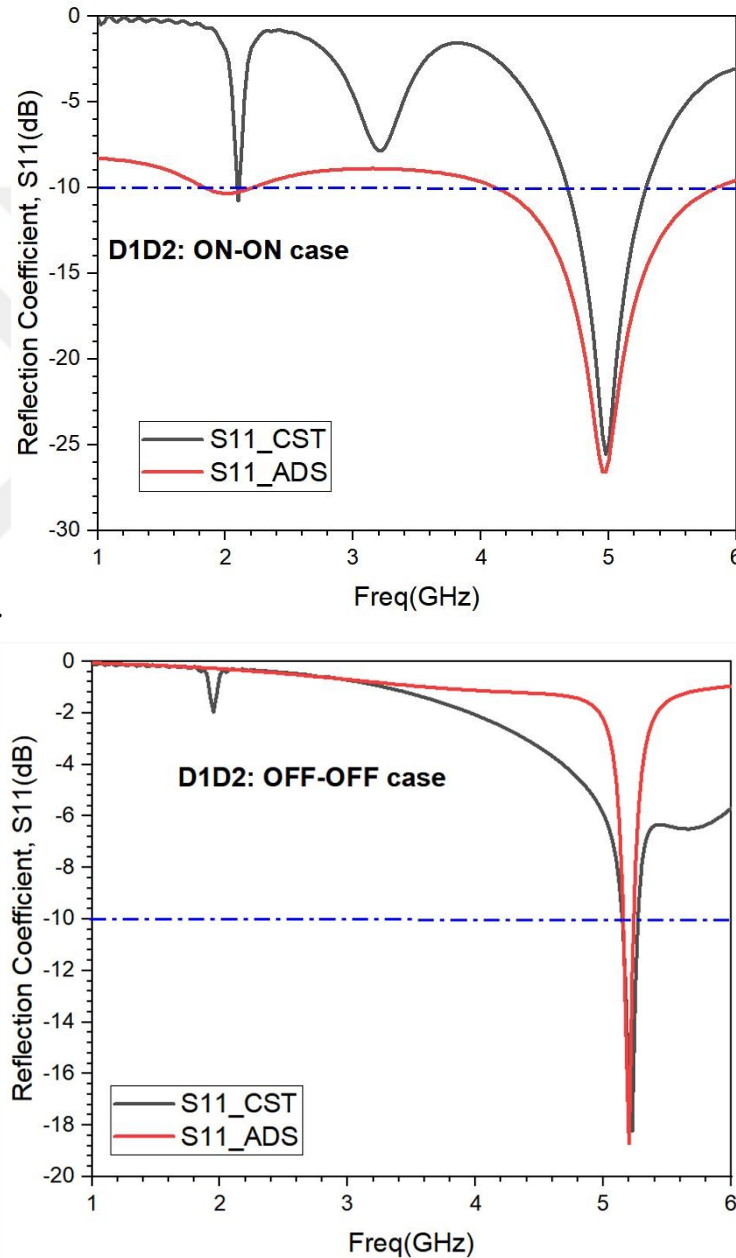


Figure 3.3. The reflection coefficients of the proposed antenna with ON-ON and OFF-OFF State obtained by CST and ADS.

3.2. Fabricated Designs

Chemical etching methods are employed to fabricate the biasing circuitry, and two proposed antenna structures are created, taking advantage of their versatility and cost-effectiveness. The prototype antenna is depicted from different perspectives using digital meter measurements in Figure 3.4 (a-d), respectively. This visualization in Figure 3.4 (a-d) provides detailed description for the antenna's physical dimensions, shape, and structural characteristics. Based on this analysis, it is evident that the proposed antenna design possesses a low-profile structure, making it suitable for integration into compact wireless devices. The fabrication process validates the antenna's performance, and the resulting prototypes provide valuable insights into the antenna's practical implementation and suitability for real-world applications.

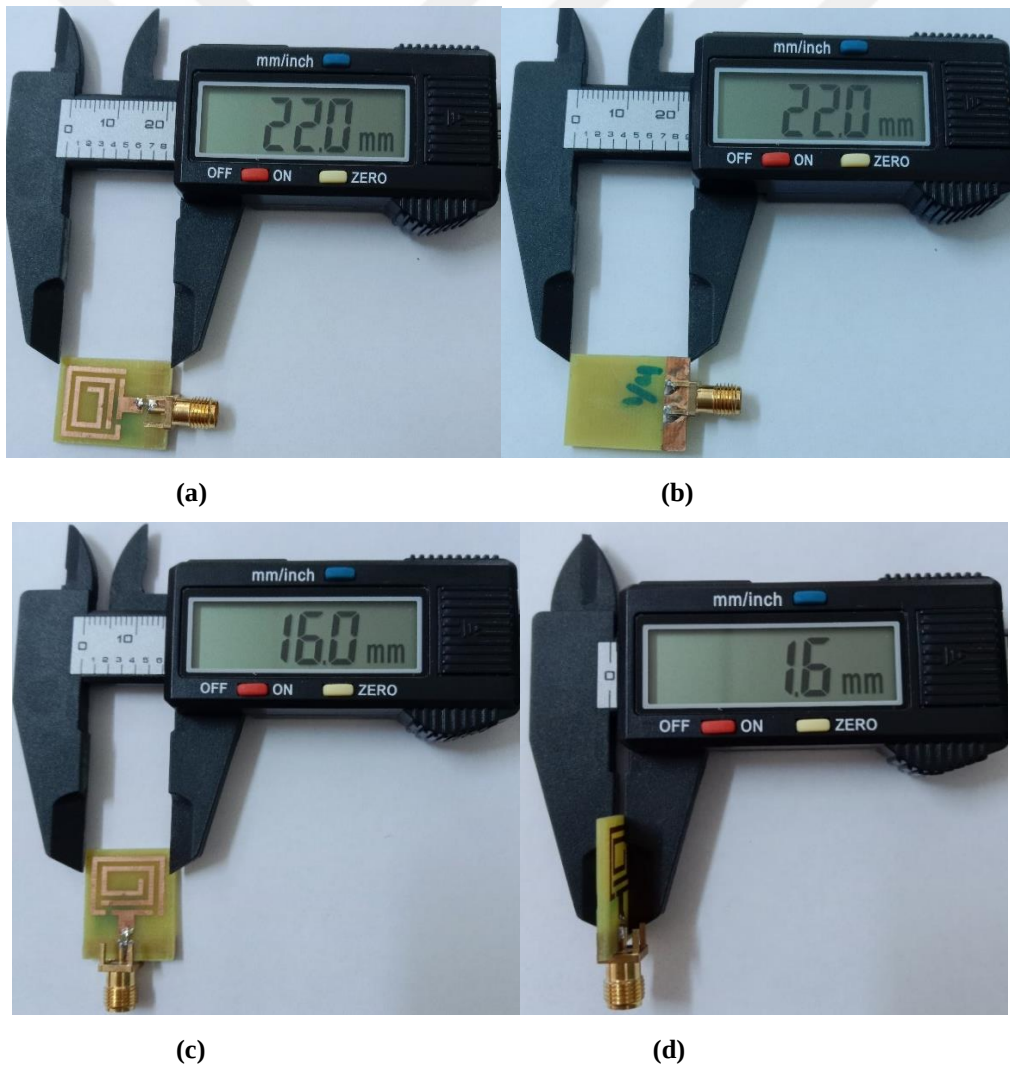
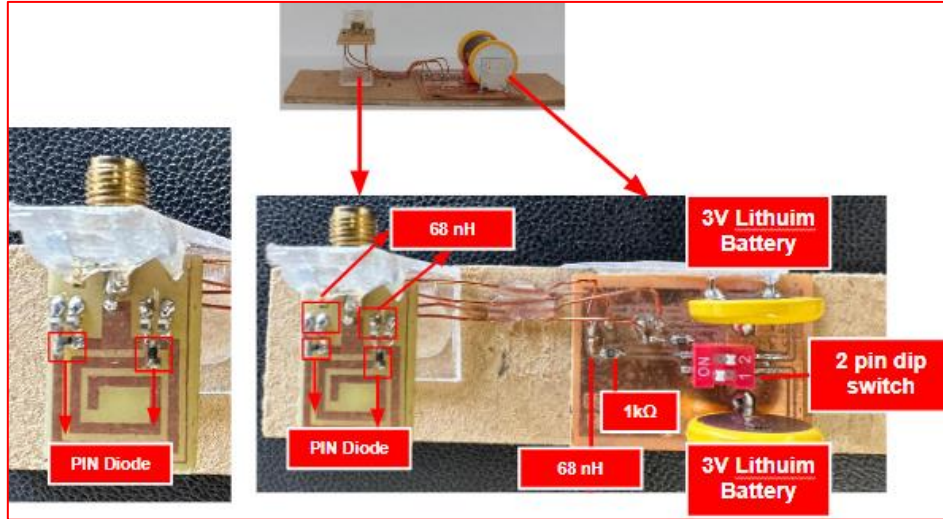
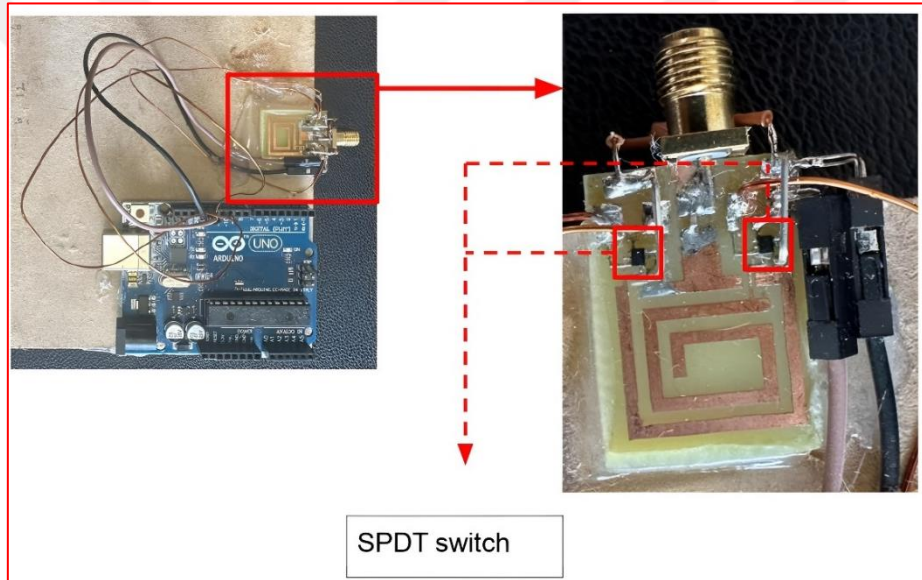


Figure 3.4. The prototype antenna with different views a) front along with the length, b) back, c) front along with the width, and d) side with the thickness

In Figure 3.5 a, the proposed antenna structure is implemented by soldering two BAR64-02V PIN diodes and a 100 pF DC Block Capacitor into the corresponding gaps of the antenna. These PIN diodes act as the switching components responsible for the reconfigurability of the antenna, allowing the control of its operating states. The DC Block Capacitor is used to separate the DC and RF signals, preventing interference and ensuring accurate comparison between the numerically calculated and measured results. Additionally, Figure 3.5 a illustrates the implementation of the biasing circuitry, which is an integral part of the antenna design. The biasing network includes two CR2032 - 3 Pin Vertical 3V Lithium Batteries, a 2 PIN Dip Switch, a 68 nH inductor, and a 1 k Ω resistor. Figure 3.5 b further demonstrates the proposed antenna with an RF switch controlled by ARDUINO. The DC Block Capacitor with a value of 100 pF is also utilized in this design, as depicted in Figure 3.5 b. This implementation ensures proper functionality and control of the reconfigurable antenna, facilitating the experimental validation of its performance.



(a)



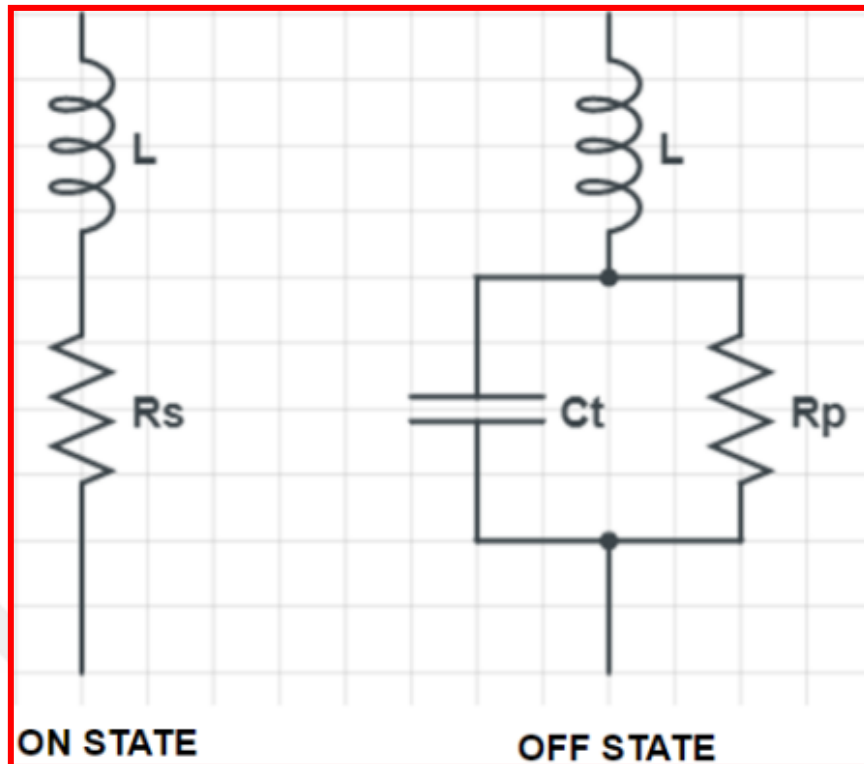
(b)

Figure 3.5. a) Prototype 1 along with BAR64-02V, b) Prototype 2 along with SPDT switches of CG2415M6.

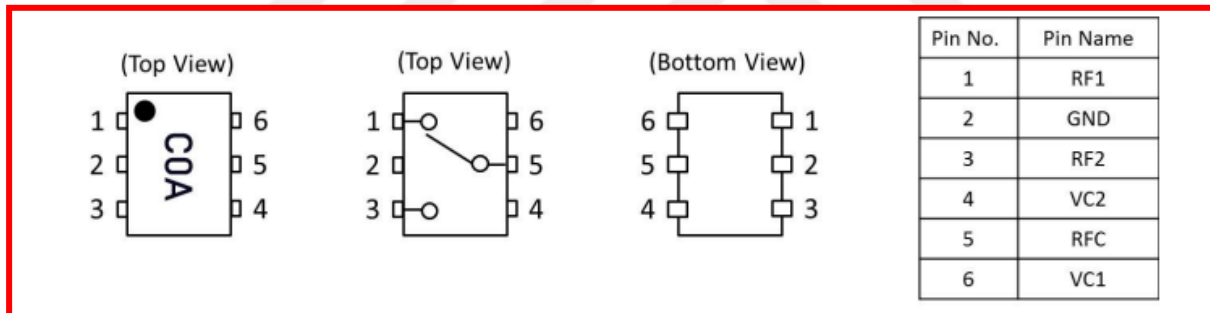
The essential aim for the designing and analysis of the frequency reconfigurable antenna is to understand the equivalent circuit behavior of the PIN diode. The equivalent circuit model of the BAR6402V PIN diode is shown in Figure 3.6 a. When the PIN diode is forward-biased, it behaves as a series combination of low resistance and inductor, allowing current flow (ON state). On the other hand, in the reverse-biased condition, it exhibits a parallel combination of high resistance and capacitor, in series with the inductor (OFF state). Likewise, having knowledge about the block diagram and evaluation circuit of SPDT switches, such as the

CG2415M6, is crucial for frequency reconfigurable antenna design. This knowledge empowers designers to understand the switch's functionality, control mechanisms, and performance characteristics, facilitating proper signal routing, control, power handling, and performance evaluation. Figure 3.6 b represents the truth table and block diagram of the CG2415M6 SPDT switch.

An SPDT switch consists of three terminals: a common terminal (COM) and two output terminals - normally open (NO) and normally closed (NC). In its initial state, the COM terminal is linked to the NC terminal. When the switch is activated, this connection alters, causing the COM terminal to connect with the NO terminal. This switch functionality facilitates the selection between distinct circuits or pathways within a circuit, providing adaptability in routing signals. In this thesis, the COM terminal of the SPDT switch is linked to a digital input pin on the Arduino Uno. Simultaneously, the NO terminal is connected to the Arduino's 3V power source, and the NC terminal is attached to the Arduino's ground (GND). Based on the state of the switch, specific code is written to execute defined actions, govern other components, or make decisions within the Arduino program. This setup enables remote control and monitoring of the frequency reconfigurable antenna using the Arduino Uno and IoT-oriented technology.



(a)



VC1	VC2	RFC-RF1	RFC-RF2
High	Low	ON	OFF
Low	High	OFF	ON

(b)

Figure 3.6. a) The PIN diode BAR6402V represented by an equivalent circuit, b) The SPDT switch CG2415M6 depicted with a block diagram [225].

3.3. Results and Discussions

3.3.1. Simulation Results

The proposed antenna structure is simulated with four different configurations to analyze how the switch states impact the operating frequencies and resonance frequencies. The simulation results are presented in Figure 3.7, showing the reflection coefficients of the antenna with and without switches. The figure clearly demonstrates that changing the switch states has a significant effect on the frequencies at which the antenna operates and resonates.

In Figure 3.8, the radiation efficiency parameter of the proposed antenna is shown for various configurations. Radiation efficiency is a crucial metric that indicates the performance, signal strength range, and power efficiency of the system. The results reveal that despite its compact size, the proposed antenna is well-suited for sub-6 GHz applications, making it a strong candidate for such uses. However, the radiation efficiency of the OFF-ON state is not explicitly provided in Figure 8 due to the influence of spiral resonators on the antenna's non-radiation characteristics, particularly in applications below 6 GHz. The focus of Figure 3.8 is to illustrate other relevant states related to the antenna's performance, such as the reflection coefficient and bandwidth.

Table 3.2 provides a comprehensive overview of the antenna's performance parameters and their corresponding application areas for all configurations. This table reinforces the notion that the proposed design exhibits promising characteristics for sub-6 GHz applications. The performance metrics showcased in the table highlight the antenna's suitability for a wide range of applications within this frequency range.

By presenting these simulation results and performance parameters, it becomes evident that the proposed antenna design, with its versatility and compact size, holds significant potential for sub-6 GHz applications. These findings strengthen the case for further research and development efforts involving the proposed antenna. Moreover, the antenna's capability to cover various mobile and wireless communication systems further emphasizes its practicality and relevance in the current wireless landscape.

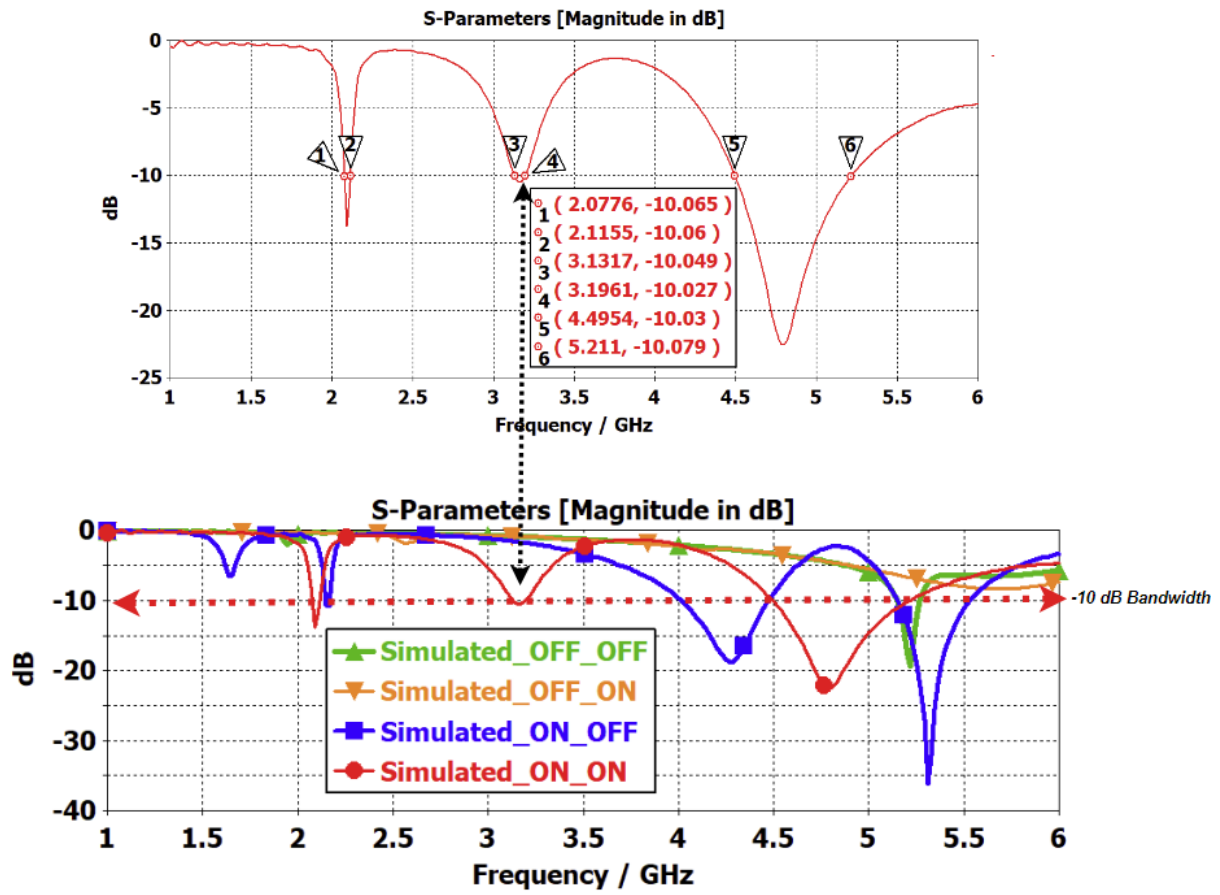


Figure 3.7. The reflection coefficient (S_{11}) of the frequency reconfigurable antenna for each configuration.

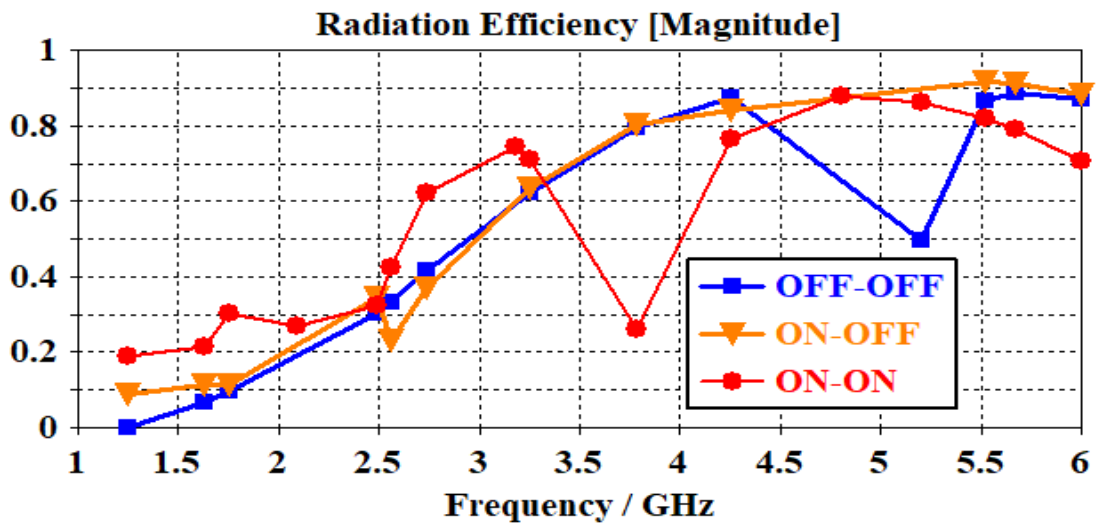


Figure 3.8. Radiation efficiency of the proposed frequency reconfigurable antenna for each configuration.

Table 3.2. Performance parameters of frequency reconfigurable antenna for each switch configuration

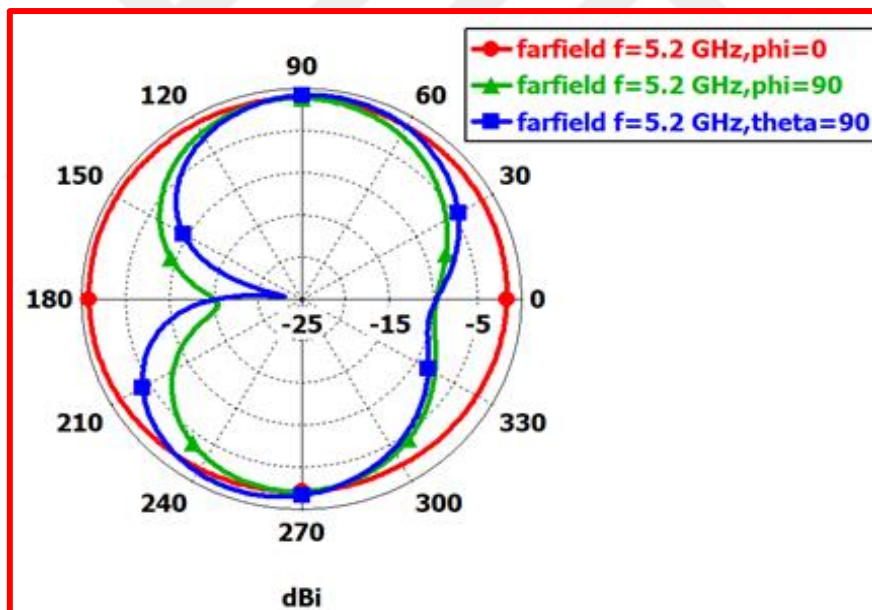
States		Operating Frequency Range (GHz)	Resonance Frequencies (GHz)	Radiation Efficiency	Application
D1	D2				
OFF	OFF	5.15-5.27	5.2	50%	Wi-Fi (IEEE 802.11a/n/ac) Bluetooth (5GHz) Point to point microwave links Short or Medium Range Radar (Automotive Radar, Industrial Sensing, Radar-based security systems)
ON	OFF	2.14-2.17	2.15	26%	3G(UMTS) 4G(LTE) Wireless Backhaul (4G and 5G networks), Satellite Communication, Broadcast Systems
		4.02-4.47	4.3	87%	WLAN (IEEE 802.11a/n/ac/ax), Commercial Wi-Fi
		5.15-5.53	5.3	82%	
ON	ON	2.08-2.11	2.09	27%	5G NR (n1 Band), IoT
		3.13-3.2	3.16	74%	Wi-Fi Access Points (5 GHz)
		4.49-5.2	4.8	88%	Bluetooth (5GHz)

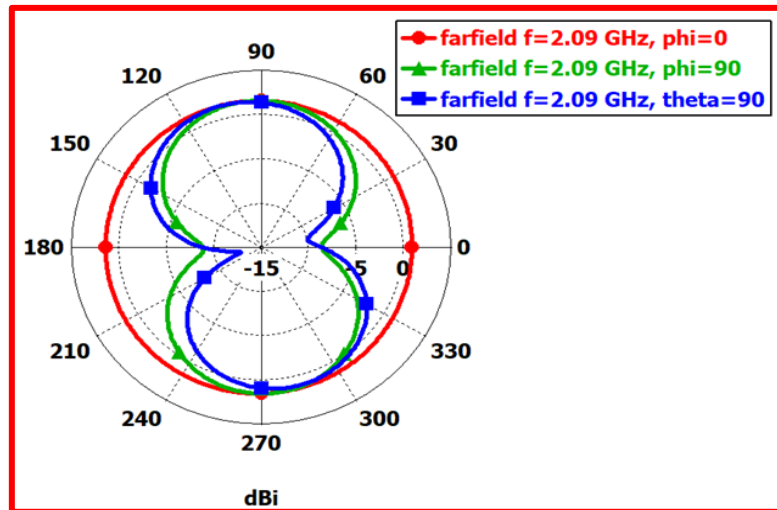
Figure 3.9 displays the radiation patterns of the proposed antenna at the resonance frequencies under three different conditions. The radiation patterns exhibit nearly omnidirectional characteristics within the frequency range of interest. An omnidirectional radiation pattern

means that the antenna emits energy uniformly in all directions around its axis, with minimal variations in signal strength across different azimuthal angles.

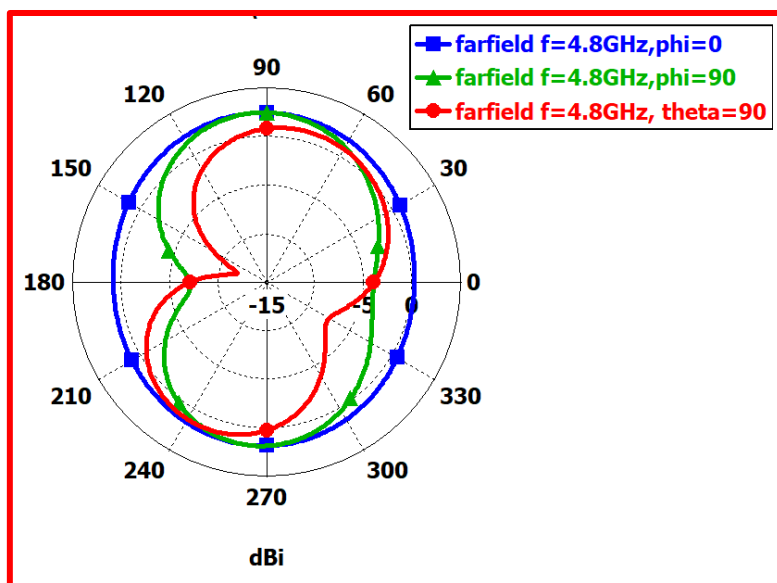
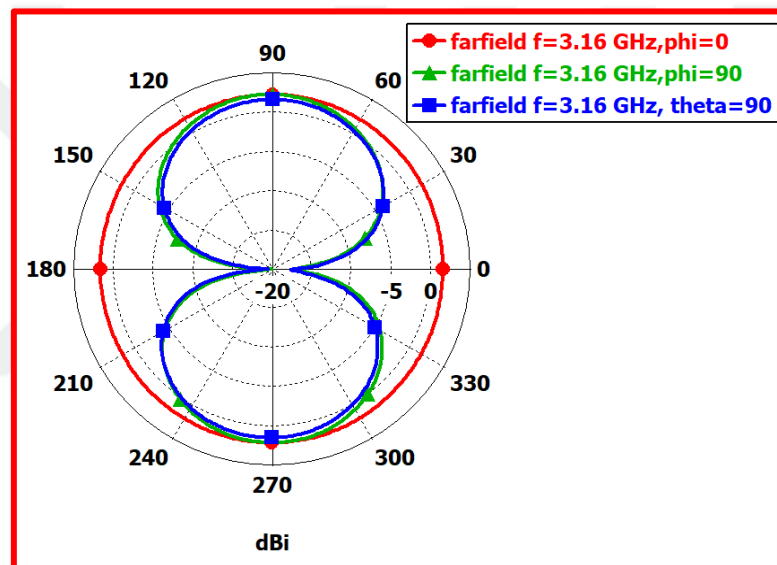
The omnidirectional radiation pattern is highly advantageous for wireless communication systems as it enables devices to receive signals from the antenna regardless of their relative orientation. In practical scenarios, where devices may be moving or positioned in various orientations, an omnidirectional antenna ensures consistent and reliable signal reception from any direction. This feature is particularly crucial in situations where wireless devices need to maintain continuous connectivity with a central access point or base station, regardless of their positioning.

The proposed antenna's ability to exhibit omnidirectional radiation patterns further enhances its suitability and effectiveness for various wireless communication applications, where seamless and reliable connectivity is of utmost importance.

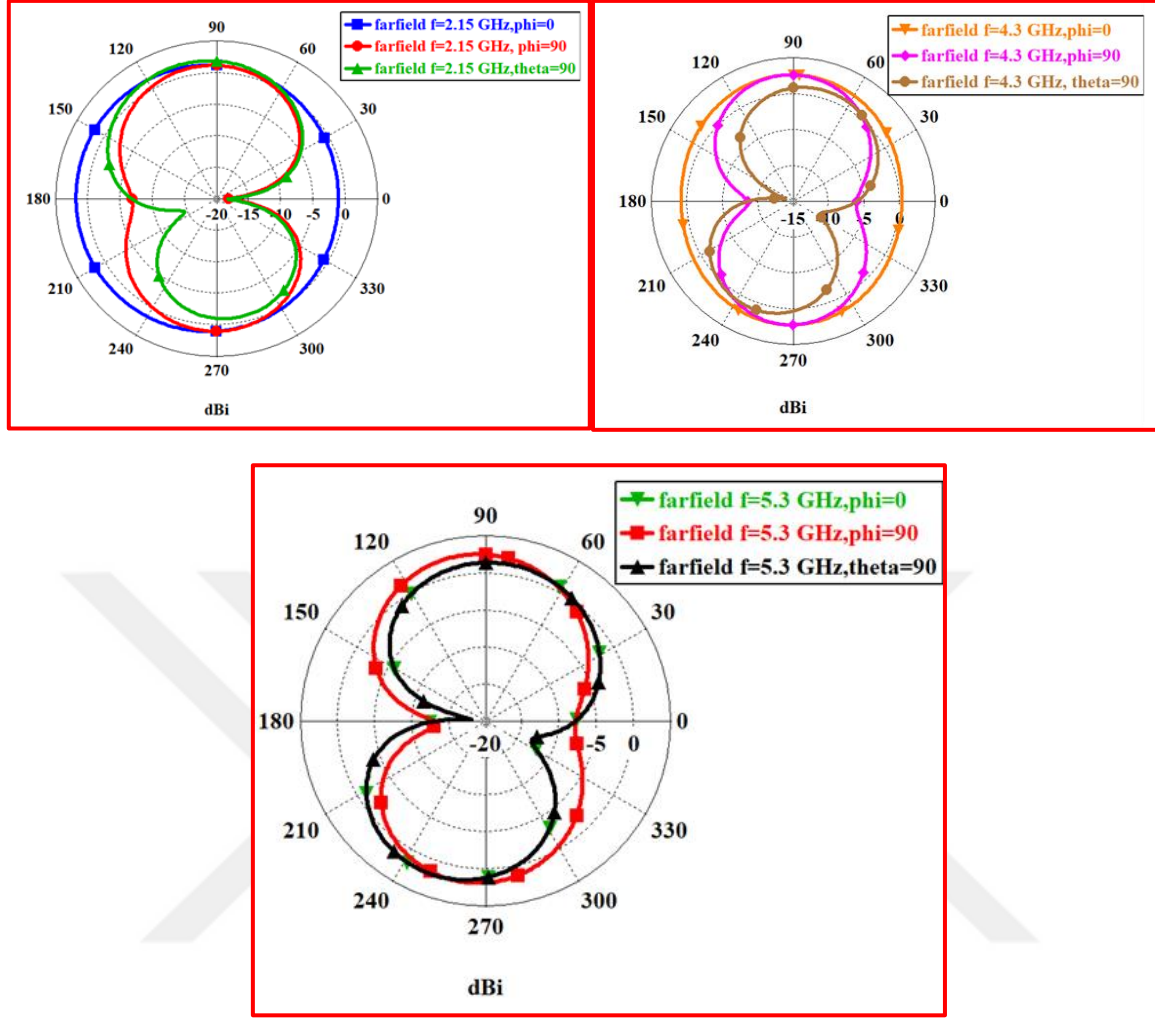




(a)



(b)



(c)

Figure 3.9. Radiation pattern characteristics for PIN diode states at their resonance frequencies: a) State 1, b) State 2, and c) State 3

3.3.2. Measurement Results

The experimental setups are used to validate the proposed antenna with PIN diodes and SPDT switches, as shown in Figure 3.10. The primary objective of the experimental process is to ensure that the physically fabricated antenna aligns with the intended design specifications. Measurement results for the fabricated antenna in different states are obtained in terms of reflection coefficients and compared to the numerically calculated results, as presented in Figures 3.11 (a-d). Figure 3.11-a show the measured and simulated reflection coefficient for the OFF-OFF configuration. The resonance frequency is found to be nearly identical in both simulation and measurement results, indicating good agreement between them. However, for

the proposed antenna with PIN diodes, there is a discrepancy between the simulated and measured reflection coefficients, as evident in Figure 3.11 a. On the other hand, for the ON-ON state in Figure 3.11 b, the simulation and measurement results of the proposed antenna with SPDT switches are in good agreement, while the measurement results with PIN diodes do not match the simulation result. Figure 3.11 c illustrates the comparison of the simulation and measurement results for the proposed antenna with ON-OFF configuration. The simulation result aligns well with the measurement result of the proposed antenna with SPDT switch. Figure 3.11 d indicates that the proposed antenna configuration does not radiate in the sub-6 GHz frequency range due to the effect of the spiral resonator. The impedance variations introduced by the spiral resonator cause impedance mismatch between the resonator and the feeding network. Additionally, the addition of the spiral resonator introduces additional resonator modes, leading to undesired frequency shifts and distortions.

The measurement results of the proposed antenna with PIN diodes and SPDT switches may differ due to various factors. Firstly, PIN diodes and SPDT switches have different characteristics and switching mechanisms. PIN diodes generally have slower switching speeds compared to solid-state switches like SPDT switches, which can affect the antenna's performance in dynamic or fast-changing scenarios. SPDT switches are preferred for faster and more reliable switching, resulting in better overall antenna performance. Secondly, the insertion loss of the switching components varies between PIN diodes and SPDT switches. PIN diodes may introduce higher insertion loss compared to SPDT switches, impacting the antenna's efficiency and gain. Furthermore, PIN diodes and SPDT switches have different RF impedance characteristics, which affect the matching network and impedance matching of the antenna. If the impedance is not properly matched, it can lead to signal reflections, reduced power transfer, and degraded antenna performance. The control circuitry for PIN diodes and SPDT switches may also differ in complexity, biasing, and control voltages. Improperly designed or implemented control circuitry can introduce additional losses or mismatches, affecting the antenna's performance differently for PIN diodes and SPDT switches. Additionally, each switching component introduces parasitic effects such as capacitance, inductance, and resistance, which can vary between PIN diodes and SPDT switches and impact the antenna's behavior differently. Moreover, variations may occur during the chemical etching process of antenna fabrication, leading to slight differences in antenna dimensions and affecting performance parameters such as resonant frequency and impedance.

Overall, considering these factors is crucial in interpreting and understanding the differences between the measured results of the proposed antenna with PIN diodes and SPDT switches.

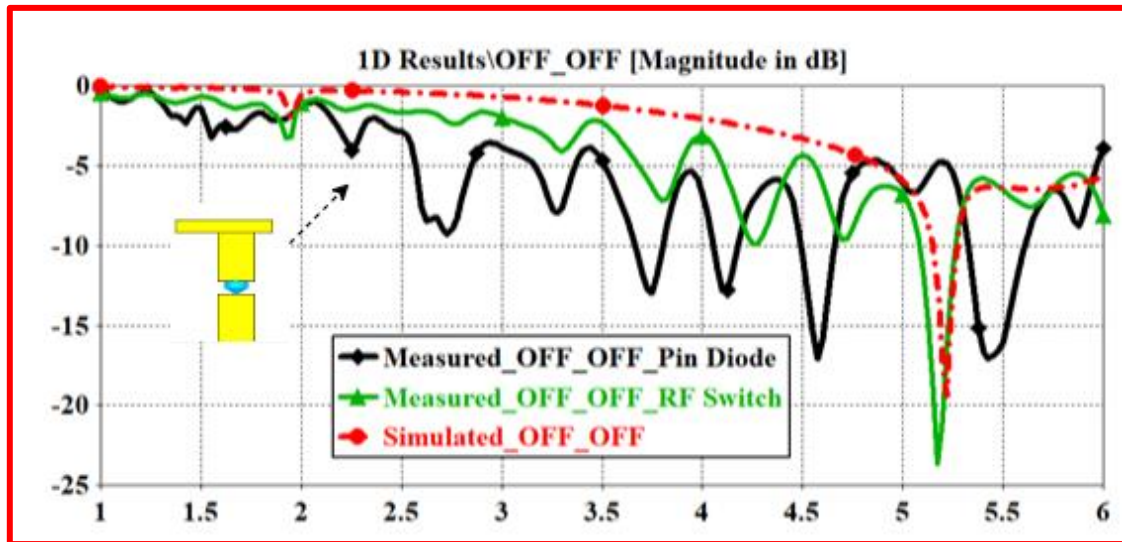


(a)

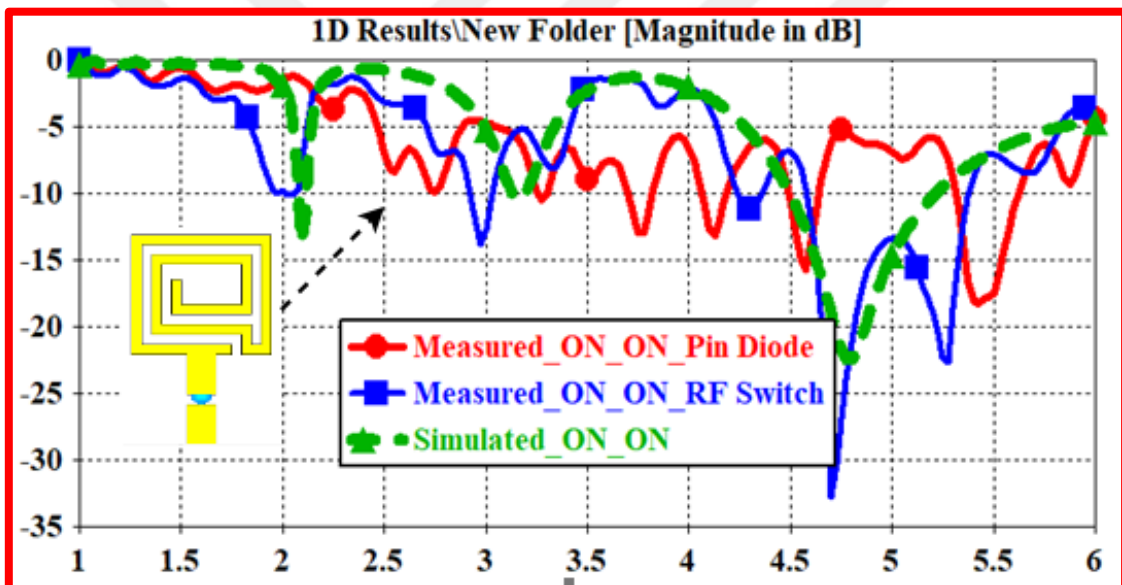


(b)

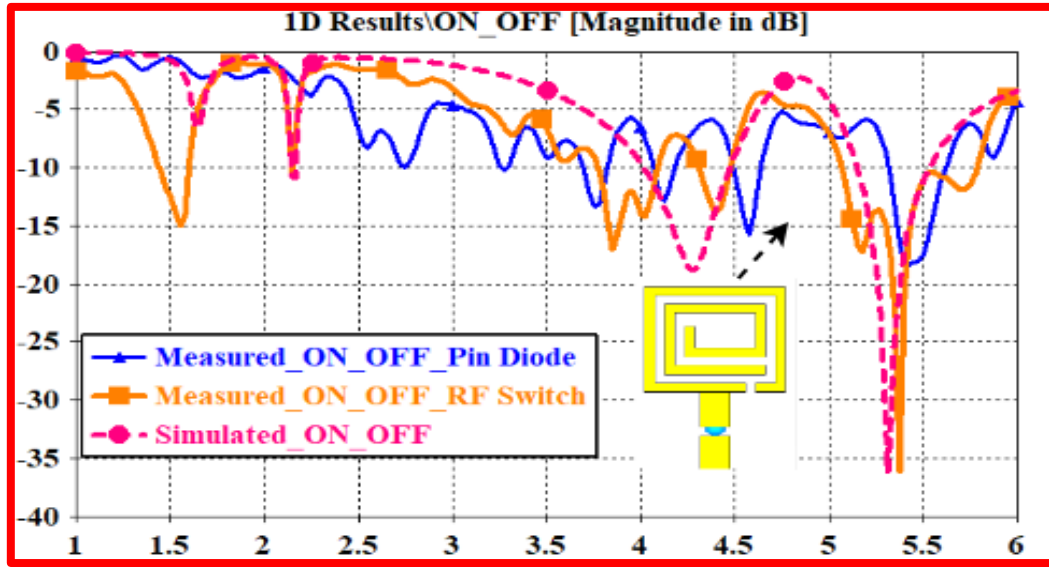
Figure 3.10. The experimental arrangement for testing the proposed antenna by a) using PIN diodes, b) employing SPDT switches.



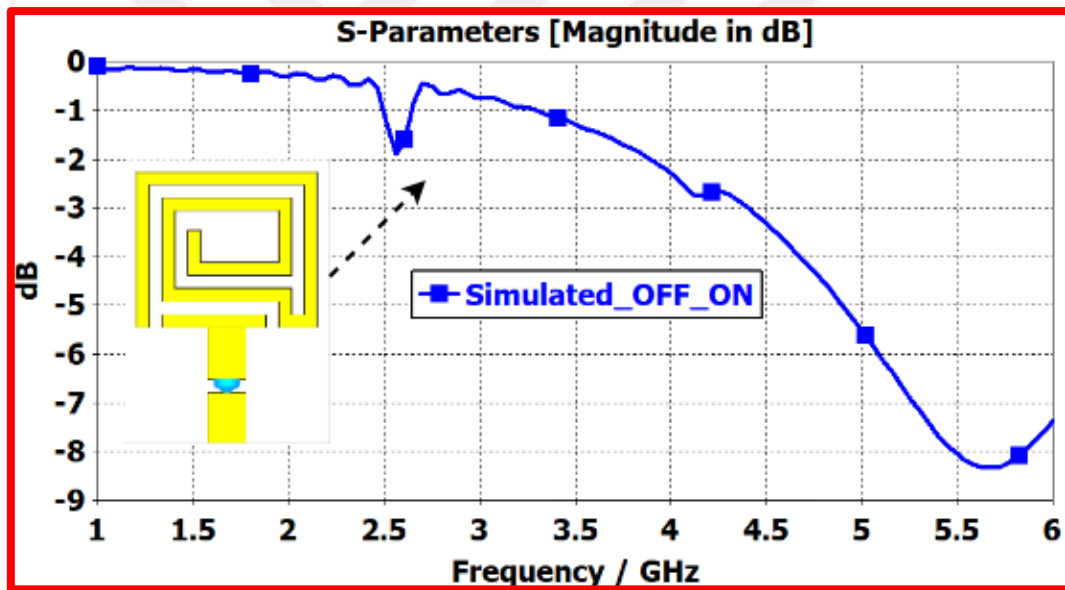
(a)



(b)



(c)



(d)

Figure 3.11. Comparison between the numerically calculated and measured reflection coefficients for the proposed antenna configurations with: a) both PIN diodes OFF, b) both PIN diodes ON, c) one PIN diode ON and the other OFF, and d) one PIN diode OFF and the other ON.

Table 3.3 lists the novel antenna structure proposed in this study along with other frequency reconfigurable antennas presented in the existing literature. The data given in Table 3 indicates that the proposed antenna exhibits a better performance compared to its counterparts

in the literature, particularly in terms of compactness, wide operating frequency range, and cost-effectiveness. Furthermore, the comparison also includes the control methods employed by the utilized components, which ensure the reconfigurability features. Notably, the proposed antenna's reconfigurability mechanism is also evaluated within this context. The small size and easily control mechanism features of this novel antenna make it a good candidate for various applications. This includes access points, gateways, smartphones, and IoT kits, all of which benefit from its reduced size and simple control approach.



Table 3.3. Comparison of the proposed antenna with other frequency reconfigurable antenna studies in the literature

Ref	Dimension (mm²)	Reconfigurable Technique (#)	Components Control Method	Frequency Range GHz
[226]	120x60	Varactor Diode (1)	Manually	1.3 - 2.6
[227]	27x25	PIN Diode (3)	Manually	2.29–2.39 / 4.40–4.52 / 4.29– 4.57 / 5.71–5.93 / 2.3–2.4 / 5.64–5.96
[228]	50x50	PIN Diodes (2)	IoT Based NodemCU Unit	2 -5 / 2 - 3.7 / 1.8 - 3.4 / 1-3.7
[229]	25x32	Utilizing slots in the radiating patch	Manually	2.85–5.35 / 2.35–2.5 / 3.18– 3.82 / 4.15–5.42
[230]	70x70	Varactor Diode (2)	Manually	2.45 -3.55
[231]	36x14	PIN Diode (2)	Manually	2.03-2.17 (ON) 2.37-2.51 (OFF)
[232]	50x45	PIN Diode (2)	Manually	2.2-6
[233]	30x28	PIN Diode (1)	Manually	1.7–1.9 / 2.7–3 / 5.7–5.9 / 8.8– 9.5 / 5.6–6.1 / 9.3–9.6
[234]	30x30	PIN Diode (2)	Manually	1.8 - 4.5
[235]	48.19x38.36	Variable Capacitance (6)	Manually	2.41 - 5.27
[236]	33x16	PIN Diodes (3)	Manually	2.1 - 5.2
[237]	15.5x32	PIN Diodes (3)	Microcont roller based IoT device	2.01–2.16 / 3.189–3.589 / 3.13–3.61 / 2.97–3.54 / 2.81– 3.18 / 2.59–2.99
This work	22x16	PIN Diodes (2) or RF Switch (2)	Manually or Arduino	2.08 – 5.53

4. EXPLORING ADD-DROP RESONATOR INTEGRATION AND SPDT SWITCH FOR ENHANCED FREQUENCY-RECONFIGURABLE MICROSTRIP ANTENNAS IN MULTIBAND COMMUNICATION SYSTEMS

4.1. Ring Resonators

In 1969, Marcatili introduced a standard configuration for bandpass filters using integrated ring resonators [238]. The layout of the channel dropping filter proposed by Marcatili consists of two straight waveguides, also known as bus or port waveguides, coupled to the ring resonator through either directional coupler using the evanescent field or multimode interference (MMI) couplers. A simplified version of the filter, called a "notch" filter, can be obtained by removing one of the bus waveguides, resulting in a unique filter characteristic. By adding additional bus waveguides and ring resonators, multiple coupled ring resonator filters can be constructed.

Yariv described the basic configuration of a ring resonator channel dropping filter [239, 240]. This setup involves unidirectional coupling between a ring resonator with a radius of " r " and a waveguide. The model assumes that a single unidirectional mode of the resonator is excited, and the coupling is assumed to be lossless. It considers only a single polarization and assumes that the waveguide segments and coupler elements do not couple waves of different polarizations. To account for various types of losses encountered during light propagation in the ring resonator filter, these losses are incorporated into the attenuation constant. The interaction between the waveguide and the ring resonator is mathematically described using a matrix relation, given by Equation 4.1.

In summary, Marcatili's configuration using integrated ring resonators has become a standard approach for designing bandpass filters. By manipulating the layout and adding or removing components, various types of filters can be realized. Yariv further developed the concept, considering unidirectional coupling and losses in the ring resonator, resulting in a well-defined mathematical model for the channel dropping filter. These advancements have paved the way for the design and implementation of efficient and effective optical filters with applications in various optical communication systems and devices.

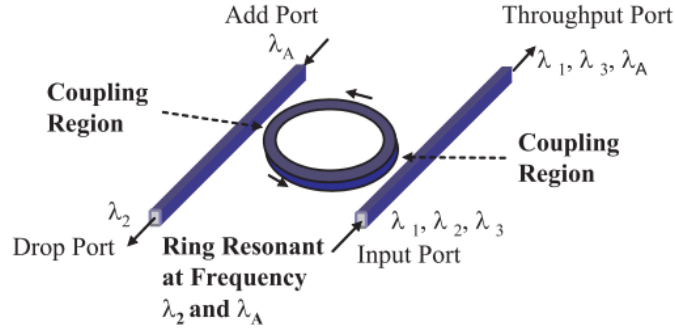


Figure 4.1. Basic ring resonator structure as drop channel filtering [238]

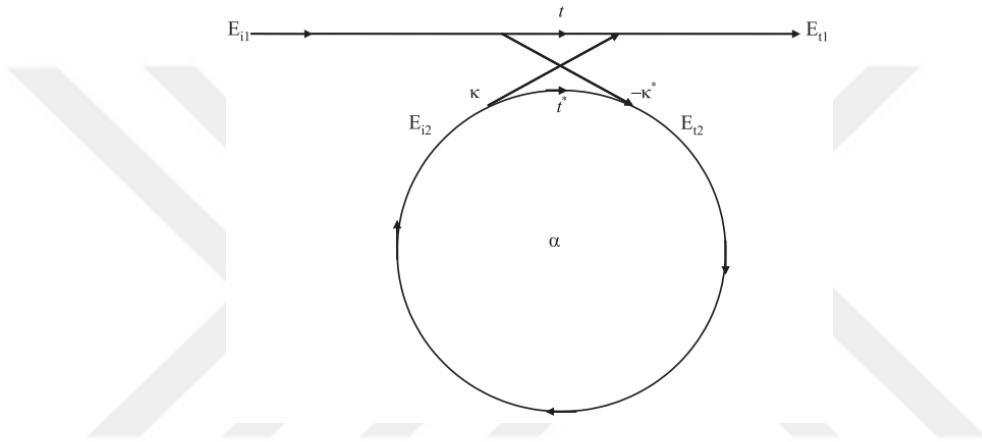


Figure 4.2. General schematic of ring resonator coupling [239]

$$\begin{pmatrix} E_{t1} \\ E_{t2} \end{pmatrix} = \begin{pmatrix} t & \kappa \\ -\kappa^* & t^* \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix} \quad (4.1)$$

The complex mode amplitudes in the system are normalized, so their squared magnitudes represent the modal power. The values of the coupler parameters t and κ are specific to the coupling mechanism used. The asterisk (*) signifies the complex conjugate of t and κ .

The matrix is symmetric because the considered networks adhere to the principle of reciprocity. This means that the coupling between two ports is the same in both directions. As a result, the matrix elements are symmetric, as shown in Equation 4.2.

$$|\kappa|^2 + |t|^2 = 1 \quad (4.2)$$

To simplify the model further, the value of E_{i1} is set to 1. This choice simplifies the analysis by fixing the initial mode amplitude at the input port of the ring resonator. With this assumption, the round trip in the ring can be described by the following Equation, which captures the behavior of the signals propagating through the ring:

$$E_{i2} = \alpha.e^{j\theta}E_{i2} \quad (4.3)$$

The loss coefficient, denoted as α , quantifies the signal attenuation or power loss within the ring. When there is no loss, α is equal to 1. The variable θ is the result of multiplying the angular frequency ω , the circumference L , and the inverse of the phase velocity c . In simpler terms, $\theta = \omega L/c$. The ring's circumference, denoted as L , is determined as $L = 2\pi r$, where r represents the radius of the ring measured from its center to the center of the waveguide. The phase velocity of the ring mode, c , is linked to the speed of light in a vacuum, c_0 , and the effective refractive index, n_{eff} . To be more precise, $c = c_0/n_{eff}$. By introducing n_{eff} into the coupling equations of the ring, a more precise depiction of the ring resonator's characteristics can be attained. The vacuum wavenumber, represented as k , is connected to the wavelength λ by the equation $k = 2\pi/\lambda$. The vacuum wavenumber signifies the spatial frequency of the electromagnetic wave. By incorporating these definitions and relationships, n_{eff} can be integrated into the coupling equations of the ring resonator, allowing for a more comprehensive description of the ring's behavior, as demonstrated in Equation 4.4.

$$\beta = k.n_{eff} = \frac{2\pi.n_{eff}}{\lambda} \quad (4.4)$$

Various types of ring resonator simulation models are explained to offer a range of options that best suit specific needs in the literature for different application areas [238]. Add-drop ring resonator, which is another configuration of the ring resonator, is made up of single input, single output waveguide, and one ring resonator structure as represented in Figure 4.3.

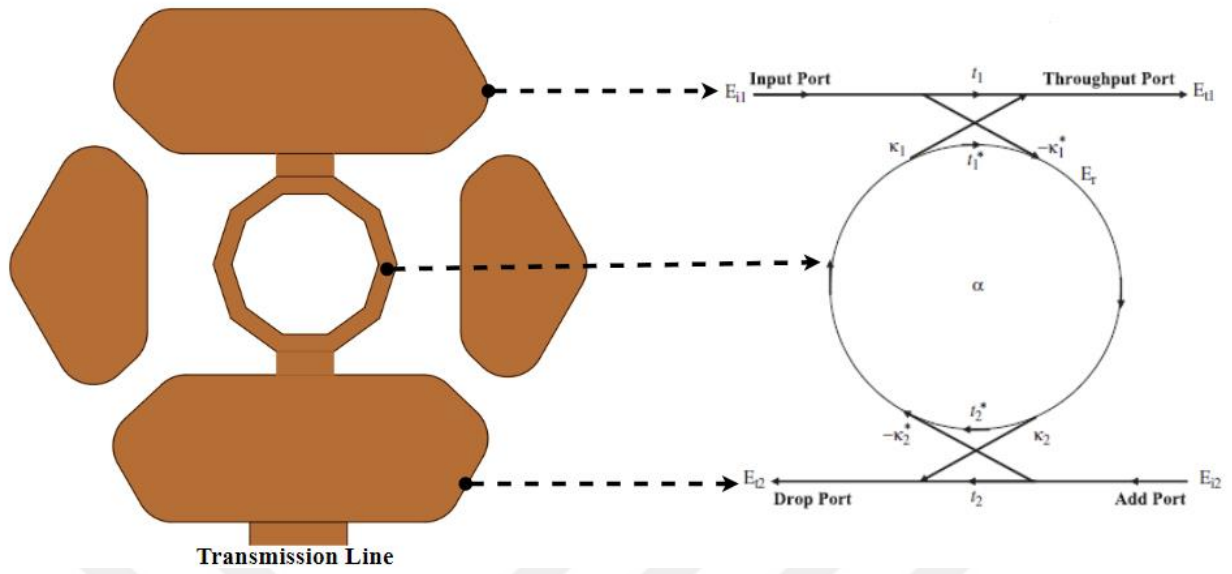


Figure 4.3. The proposed novel frequency reconfigurable antenna structure.

The add-drop ring resonator is an important component in antenna applications because it can provide frequency reconfigurability and selective filtering. These features are highly desirable in modern wireless communication systems.

- ❖ *Frequency reconfigurability:* Antennas with add-drop ring resonators can dynamically adjust their operating frequency range. This is useful in scenarios where the available frequency spectrum is limited, crowded, or subject to regulatory restrictions. By reconfiguring the resonance properties of the ring resonator, the antenna can adapt to different frequency bands, allowing for enhanced flexibility in wireless communication.
- ❖ *Selective filtering:* Add-drop ring resonator antennas can support multiple communication standards simultaneously. This is beneficial in applications where compatibility with various wireless standards, such as 5G, ISM, IoT, and Wi-Fi/Wi-Fi 6E, is required. The antenna can selectively filter and process signals from different standards, enabling seamless connectivity across diverse wireless networks.
- ❖ *Mitigation of interference:* The selective filtering functionality of the add-drop ring resonator can help mitigate interference in antenna systems. By dropping unwanted frequencies or channels, the antenna can improve the signal-to-noise ratio and suppress unwanted signals or noise sources. This capability is valuable in crowded RF environments where interference can degrade the overall system performance.

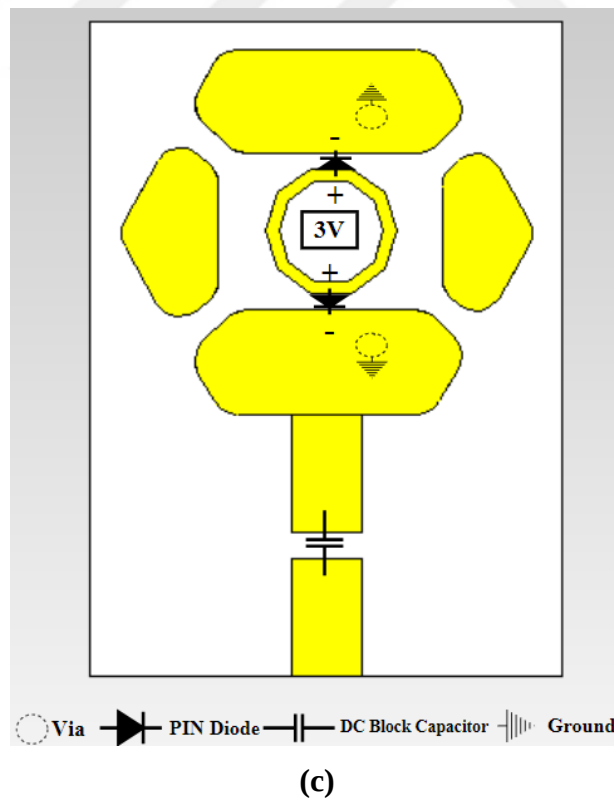
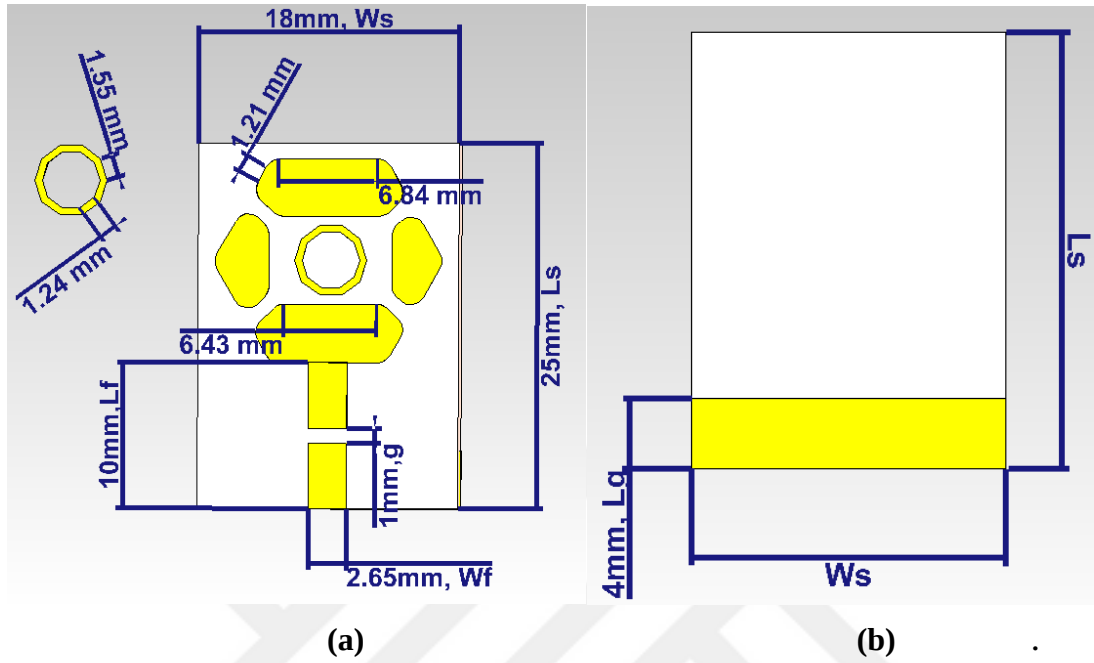
- ❖ *Compact size:* The add-drop ring resonator can be integrated into compact antenna designs without significantly increasing the antenna's size or footprint. This is essential for small form factor devices, such as smartphones, IoT devices, wearables, and wireless modules, where space is limited.

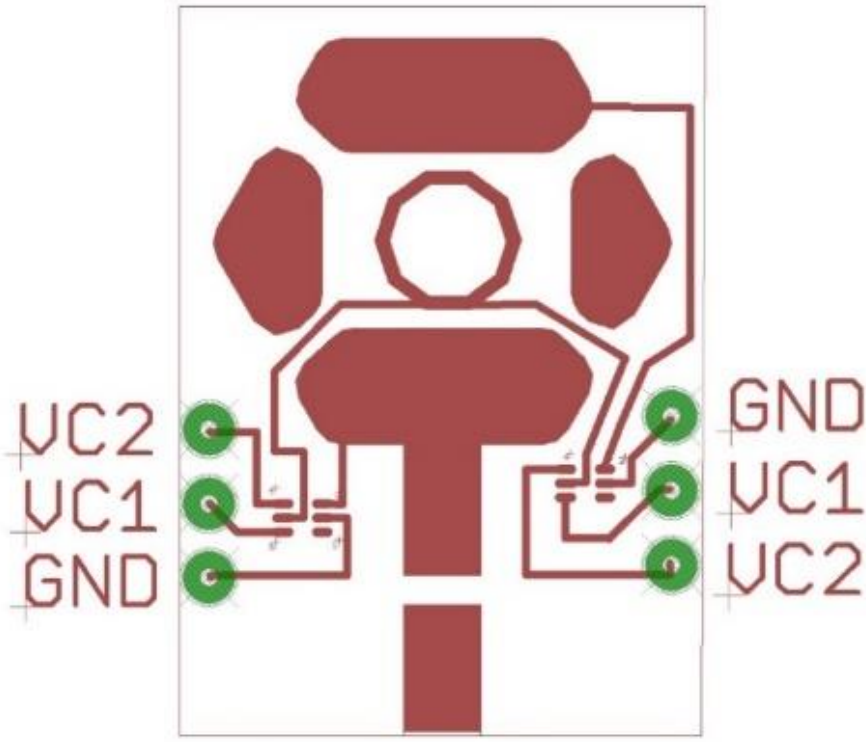
The add-drop ring resonator is a versatile component that can be used to improve the performance of antenna systems in a variety of ways. It offers the benefits of frequency reconfigurability, selective filtering, and compact size, making it a valuable tool for modern wireless communication systems. In summary, the add-drop ring resonator brings frequency reconfigurability, multi-standard support, interference mitigation, compact integration, and enhanced performance to antenna applications. It enables antennas to adapt to different frequency bands, support multiple wireless standards, suppress interference, fit into compact devices, and deliver reliable wireless connectivity in various scenarios.

4.2. Antenna Design

The novel frequency reconfigurable microstrip antenna, as depicted in Figure 4 a-d, boasts a compact design and presents front and back views for a comprehensive overview. The antenna's overall dimensions are $25 \times 18 \times 1.6 \text{ mm}^3$, as illustrated in Figure 4a, contributing to its compact form factor. The dimensions of the ring resonator are outlined in Figure 4a. To enhance impedance matching, a partial ground plane is employed. The length of this ground plane (L_g), shown in Figure 4b, is systematically varied between 3 and 6 mm, with increments of 1 mm. Following a parametric investigation, the optimal value for L_g is determined to be 4 mm, as demonstrated in Figure 4b. Additionally, Figure 4 a, b detail the dimensions of various physical parameters, including W_s (substrate width), L_s (substrate length), W_f (feed line width), L_f (feed line length), and gap (g). The schematic further presents additional dimensions in Figure 4a. The incorporation of switches is emphasized in Figure 4 c-d, specifically the use of the BAR64-02V PIN diode and the CG2415M6 model SPDT switches. These components play a pivotal role in seamlessly integrating the decagon ring resonator into the radiating portion of the antenna. The antenna's physical implementation involves an FR-4 substrate material with attributes: a relative permittivity of 4.3, loss tangent of 0.0025, and a substrate thickness of 1.6 mm. For the analysis of the antenna's performance parameters, the CST Microwave Studio program (CST MWS) is harnessed. The numerical methods such as finite integration technique (FIT) is utilized to solve and assess the antenna's performance for analysis. The simulation involves modeling the proposed antenna structure,

complete with the switching components, using copper paths. The schematic diagram of the overall antenna structure furnishes a comprehensive depiction of the design's intricacies.

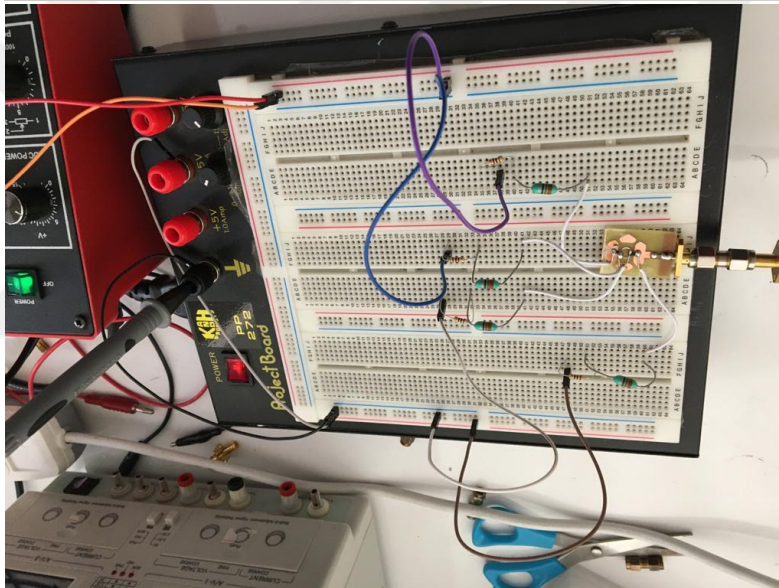
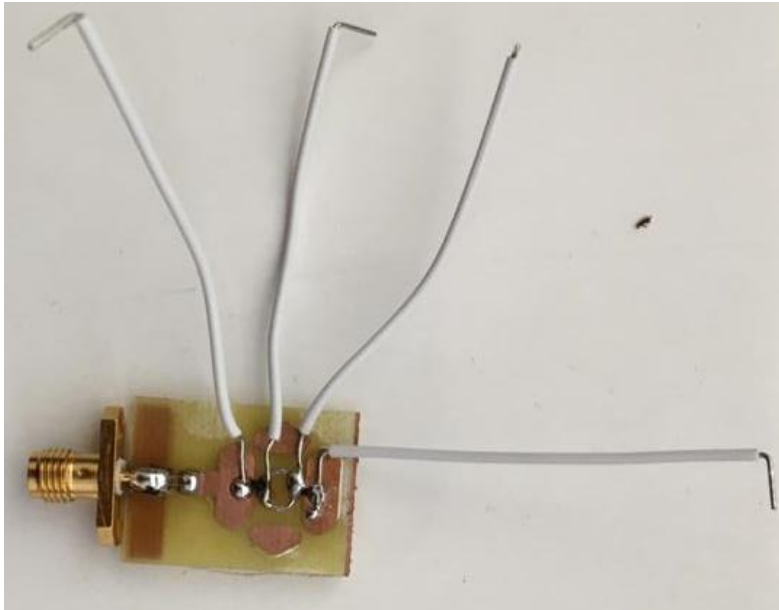




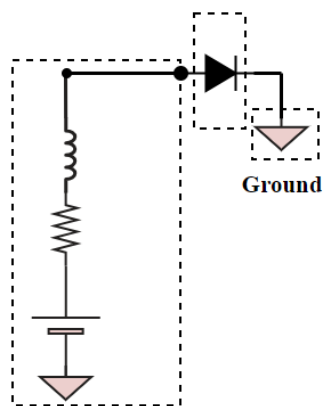
(d)

Figure 4.4. The proposed novel frequency reconfigurable antenna structure

The proposed antenna structures are separately fabricated with two different switching elements either pin diode of BAR6402-V or SPDT switches of CG2415M6 as detailed in Figure 4.5 a-b. Based on the working principle of the switching components, two different measurement setups are utilized for each approach. The equivalent circuit representation of a pin diode and the block diagram of RF switch provide a simplified model that captures the device's electrical characteristics and behavior. Therefore, Figure 4.6 is detailed to allow designers to analyze and predict the performance of the component within the antenna system. Employing the operational principles of the switching components, two distinct measurement setups are employed for each approach, as depicted in Figure 4.7 a-b.

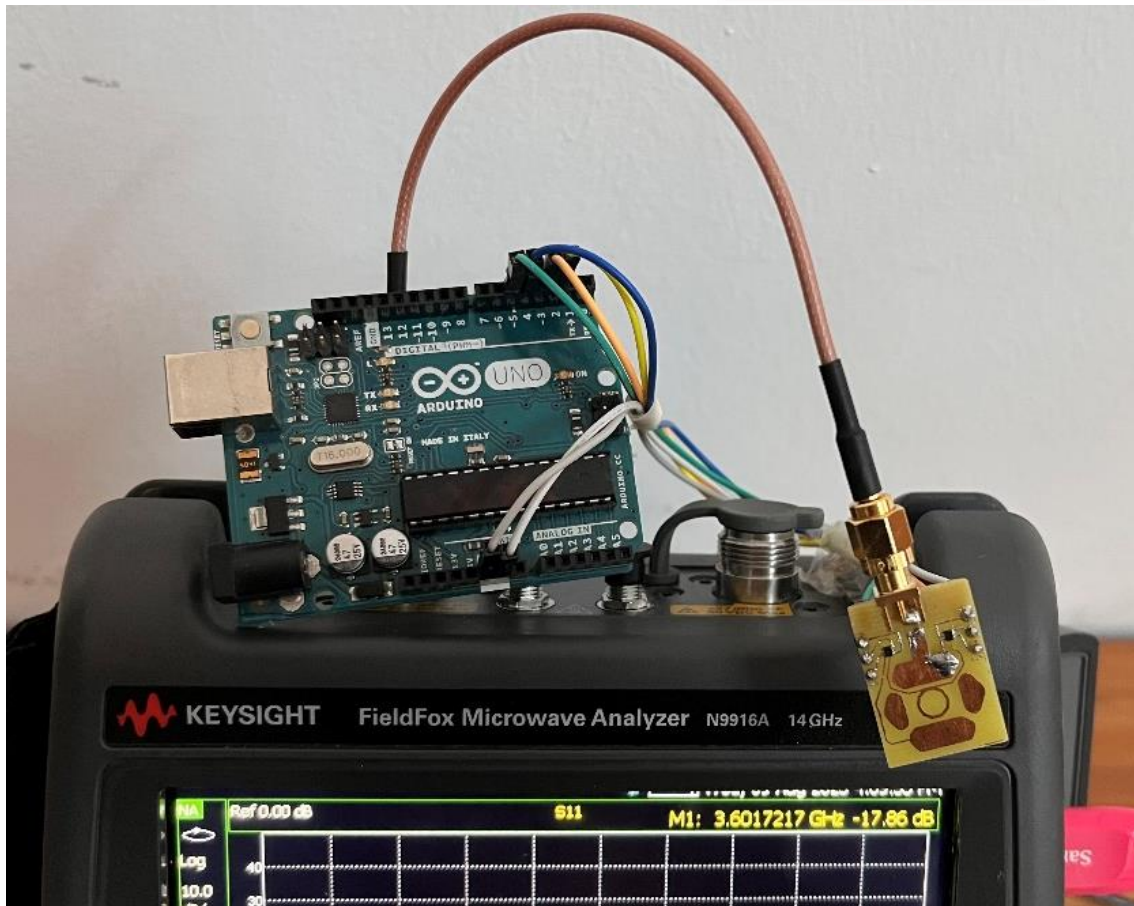
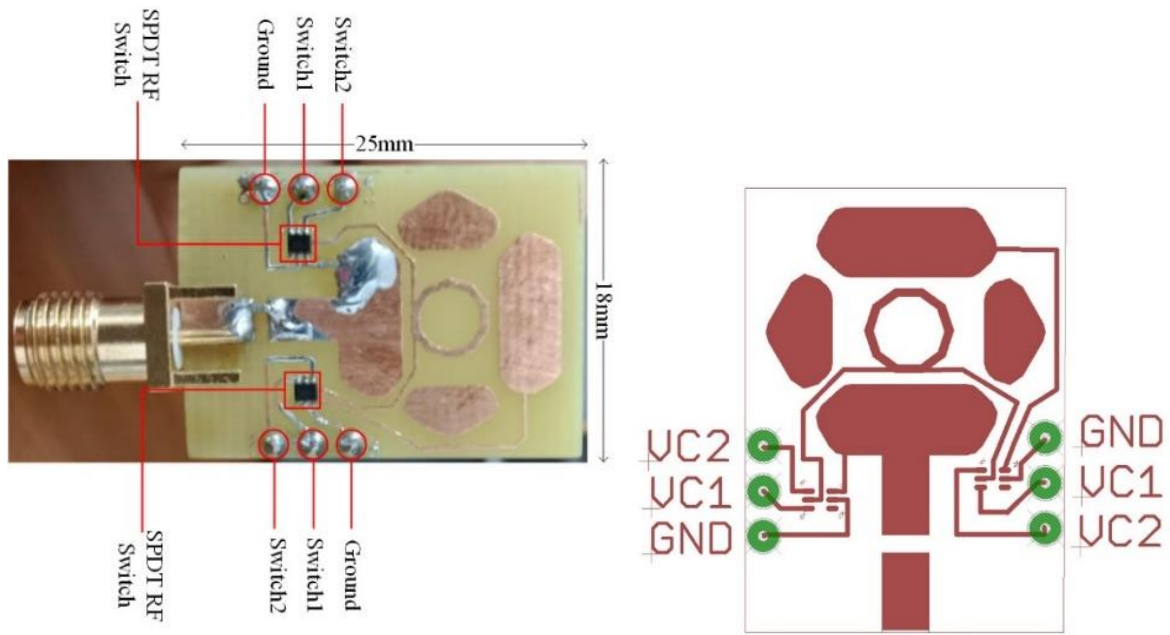


BAR6402V



Biasing Circuitry

a)



b)

Figure 4.5. The fabricated prototype antennas with a) pin diodes of BAR64-02V, and b) RF Switches of CG2415M6

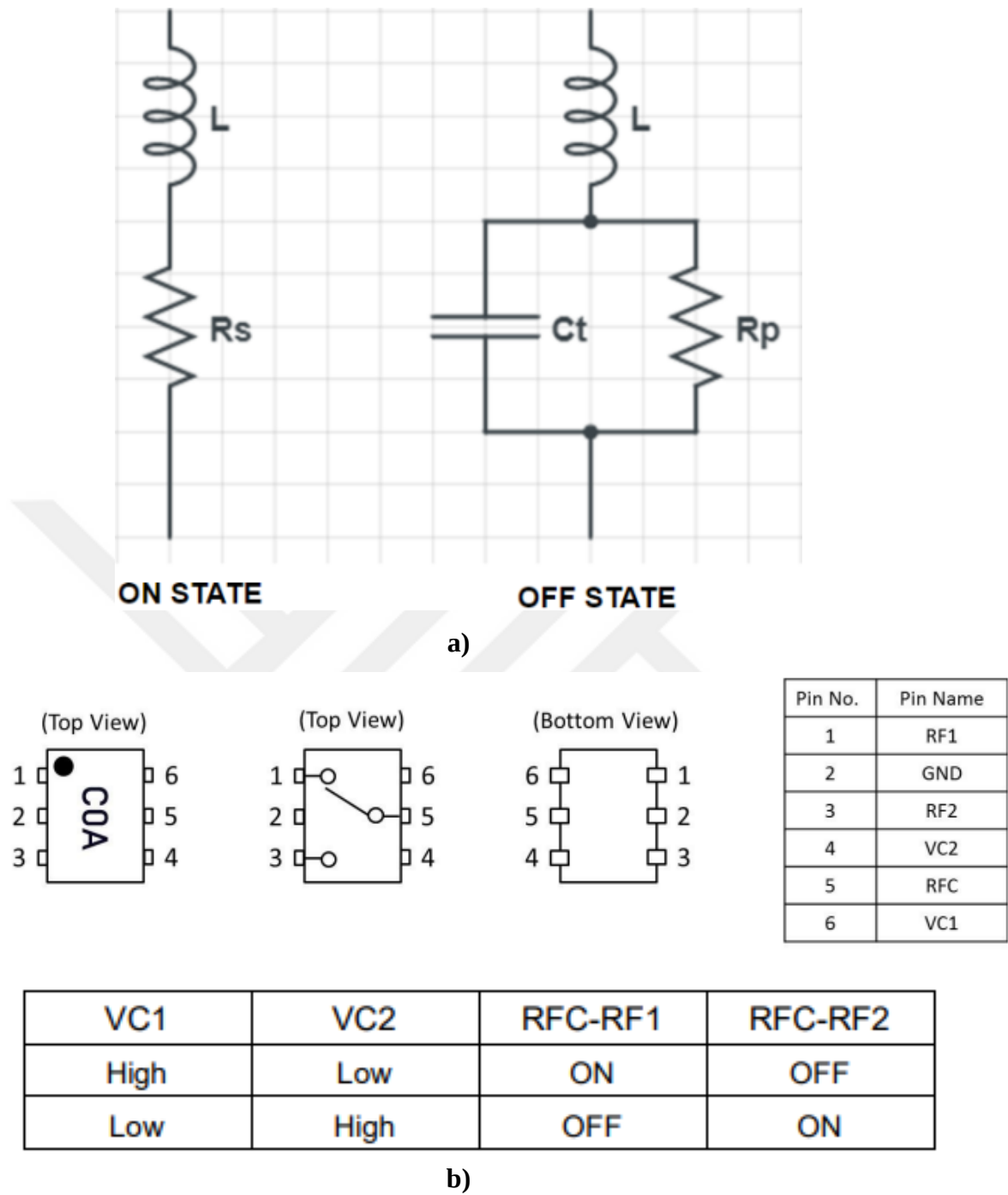
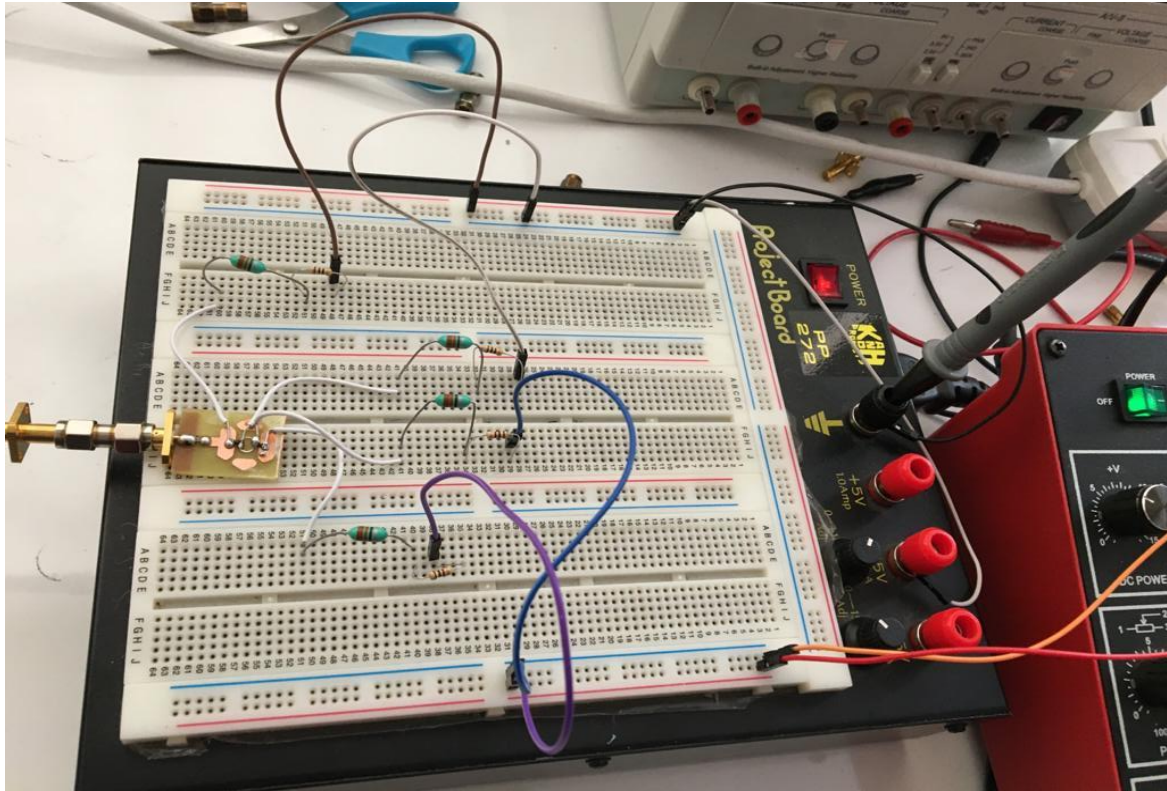


Figure 4.6. a) Equivalent Circuit Diagram of BAR64-02V, b) Block Diagram, Truth Table and Evaluation Circuit of CG2415M6



(a)



(b)

Figure 4.7. The fabricated prototype antennas with a) PIN diodes of BAR64-02V, and b) RF Switches of CG2415M6

4.3. Results and Discussions

4.3.1. Simulation Results

The proposed antenna has four different configurations determined by the states of two switching components. Figure 4.8 depicts the return loss (RL) characteristics of this antenna. It's clear from Figure 4.8 that the resonance and operating frequencies are influenced by the switch states. In State-1 (both switches are ON), the antenna exhibits a single band characteristic with a resonance frequency of 2.4 GHz. State-2 (D1 is OFF, D2 is ON) shows a single band characteristic with a resonance frequency of 3.33 GHz. State-3 (D1 is ON, D2 is OFF) results in a bandwidth from 2.59 GHz to 3.643 GHz, with a resonance frequency of 3 GHz. Lastly, State-4 (both switches are OFF) has an operating frequency band from 2.95 GHz to 4.48 GHz. Comparing these operating and resonance frequencies, there's similarity between State-1 and State-2, and between State-3 and State-4, which leads to redundancy in frequency coverage. This redundancy ensures uninterrupted communication even if one state faces interference or signal degradation due to external factors. The antenna can swiftly switch to a corresponding state with a similar band, enhancing overall system reliability. In dynamic wireless environments where the frequency spectrum changes over time, having similar operating bands in different states allows the antenna to adapt and optimize its performance based on prevailing conditions. The antenna can intelligently switch between states to select the best operating band, maximizing spectrum utilization and mitigating the effects of changing environmental factors. Depending on communication needs or scenarios, the antenna can be configured to utilize the state offering the most suitable band. For example, State-1 might be chosen for mid-band 5G communication, while State-3 could be preferred for Wi-Fi communication. This customization aligns the antenna with specific communication standards or frequency allocations. Combining the bands covered by similar states can expand the bandwidth. Utilizing both State-1 and State-2 or State-3 and State-4 simultaneously enables the antenna to operate over a broader frequency range. This expanded bandwidth is advantageous for high-data-rate applications, enhancing data throughput. The ability to switch between states with similar bands helps avoid interference from neighbouring wireless networks. By intelligently selecting the state with the least interference, the antenna optimizes its performance and maintains robust communication links. These findings illustrate the capability of the proposed antenna configurations to adapt to different frequency bands and meet the requirements of specific communication systems. Leveraging this reconfigurability,

the antenna structure offers versatile performance and allows frequency tuning for optimal operation in various wireless communication applications. Table 4.1 presents the frequency bands obtained by the four states of the antenna for different communication applications.

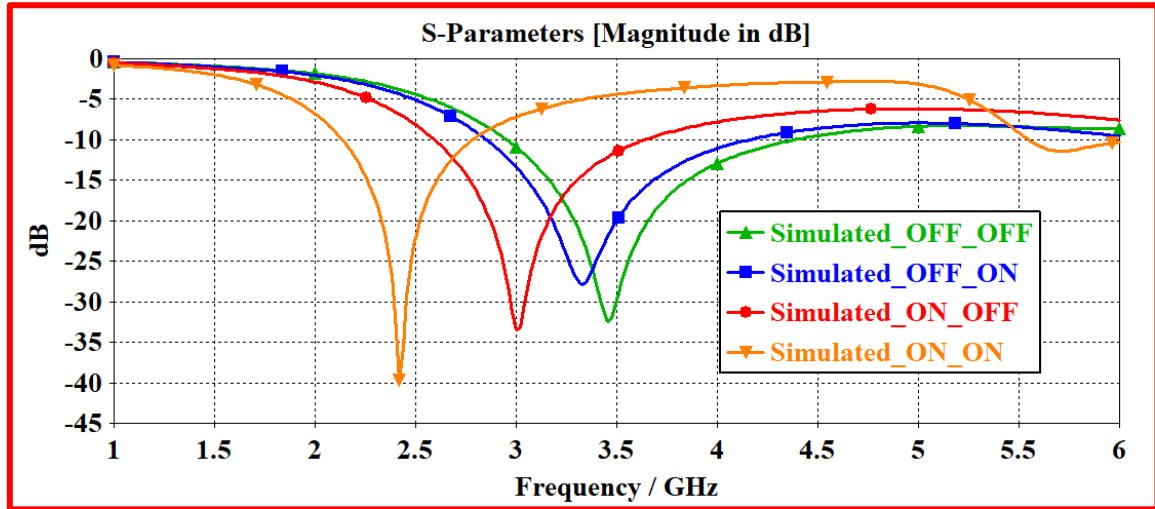


Figure 4.8. The simulated reflection coefficient (S_{11}) of the proposed frequency reconfigurable antenna

Table 4.1. RF performance parameters of frequency reconfigurable antenna for each state

State	Resonance Frequency (GHz)	Bandwidth	Suitable Communication Applications
State-1 (ON-ON)	2.4	645 MHz	Wi-Fi, Bluetooth, IoT
State-2 (OFF-ON)	3.327	1.31 GHz	Wi-Fi, Bluetooth, IoT
State-3 (ON-OFF)	3.0	1.05 GHz	Wi-Fi, Wi-Fi 6, IoT
State-4 (OFF-OFF)	3.45	1.53 GHz	5G mid-bands, Wi-Fi, Wi-Fi 6E, IoT, Cellular bands

The radiation pattern characteristics of each state of the proposed antenna, corresponding to their respective resonance frequencies, are graphically presented in Figure 4.9. It's evident from Figure 4.9 that the radiation patterns exhibit omni-directional behavior. This implies that the antenna uniformly emits electromagnetic waves in all directions within its coverage

region. The omni-directional radiation pattern holds particular significance for the communication applications mentioned earlier, such as Wi-Fi, Bluetooth, and IoT. This pattern ensures that the antenna can efficiently transmit and receive the signal, establishing dependable connectivity for devices encompassed by the coverage area. This attribute proves particularly advantageous for wireless communication systems necessitating expansive coverage, including home or office Wi-Fi networks and IoT devices distributed across diverse locales. Similarly, for applications involving 5G mid-bands, Wi-Fi 6E, and cellular bands, the omni-directional radiation pattern facilitates effective communication with multiple devices situated in varying directions. This pattern guarantees a wide coverage area, permitting seamless connectivity for mobile devices and optimizing the utilization of available frequency bands. Collectively, the omni-directional radiation pattern characteristics exhibited by the proposed antenna in each state render it ideally suited for scenarios where signal coverage, reliability, and connectivity hold paramount importance. This, in turn, facilitates uninterrupted communication across diverse directions within the designated frequency bands.

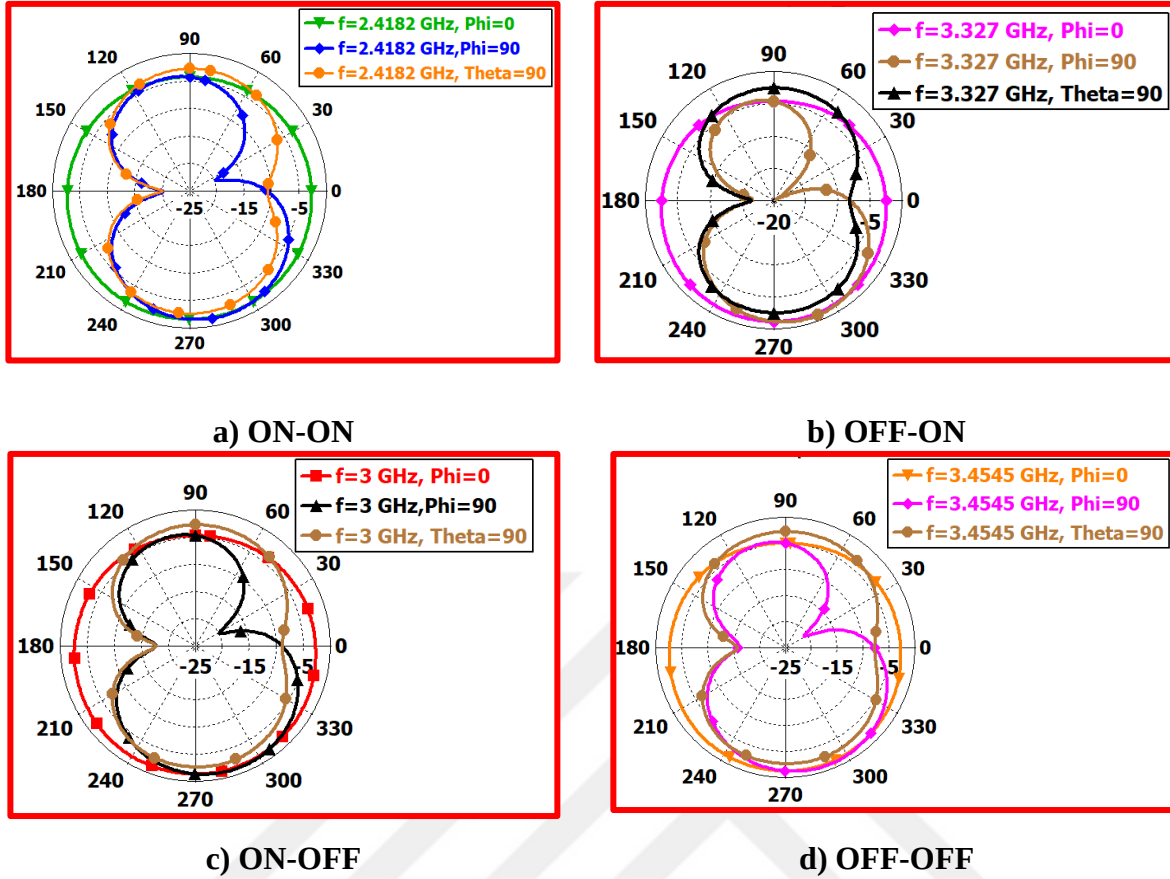


Figure 4.9. The radiation pattern characteristics of a) State-1 at 2.4 GHz, b) State-2 at 3.27 GHz, c) State-3 at 3 GHz, d) State-4 3.45 GHz of the proposed frequency reconfigurable antenna

After analyzing the operating frequency and radiation pattern characteristics of the proposed antenna, it was observed that crucial frequencies of 3GHz and 3.5 GHz were achieved for different states of the antenna, as shown in Figure 4.10. The comparison of these frequencies along with different angles was examined to determine the beamforming capability of the proposed antenna for different states. The results of this comparison, along with the main lobe magnitude direction, are presented in Table 4.2.

It is evident from Figure 4.10 and Table 4.2 that the ON-ON state is not included in the comparison, as its operating frequency does not fall within the range of 3 GHz or 3.5 GHz. The analyses further indicate that the proposed antenna structure with three states exhibits partial radiation pattern reconfigurability at 3.5 GHz with $\theta=90^\circ$. Additionally, Figure 4.11 shows the radiation efficiency of the proposed antenna for each state, providing a measure of the design's effectiveness.

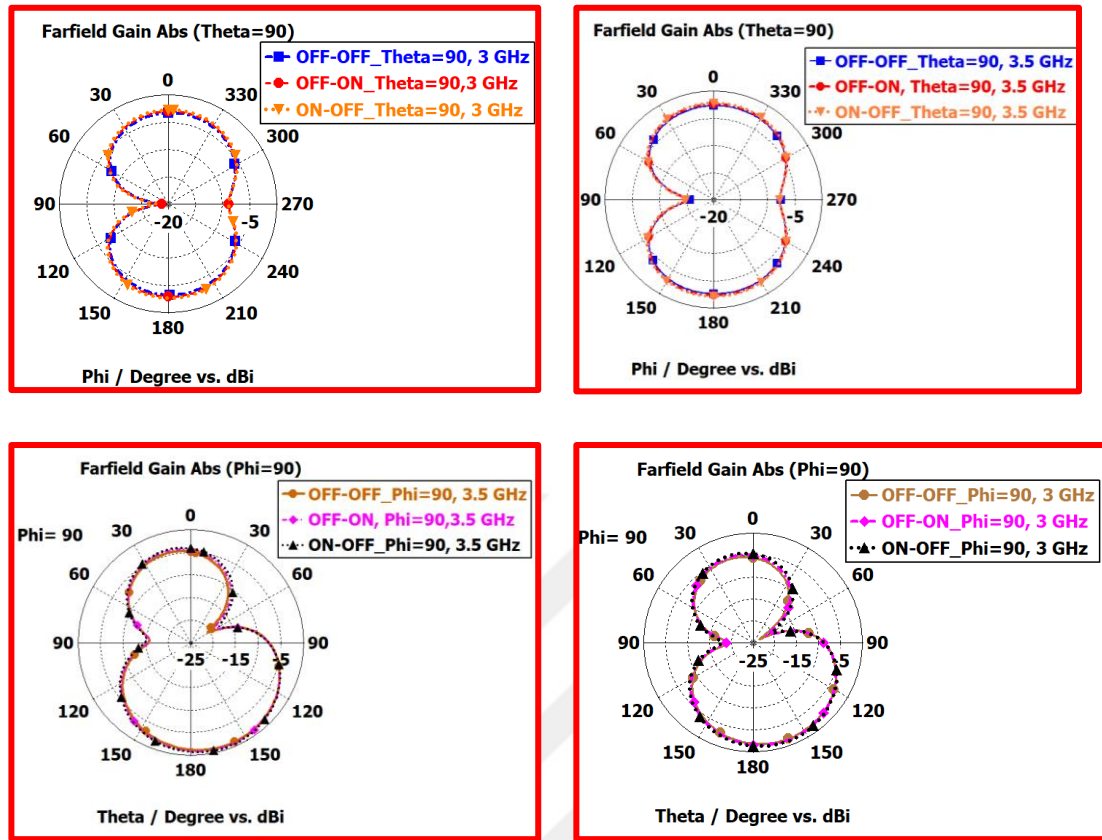


Figure 4.10. Radiation pattern characteristic for each state with different angle where $\Phi=0^\circ$, $\Phi=90^\circ$, and $\Theta=90^\circ$

Table 4.2. The main lobe magnitude direction comparison for three states.

		OFF -ON	ON-OFF	OFF-OFF
3 GHz	$\Theta=90^\circ$	185°	185°	186°
	$\Phi=0^\circ$	180°	180°	180°
	$\Phi=90^\circ$	164°	164°	162°
3.5 GHz	$\Theta=90^\circ$	186°	185°	189°
	$\Phi=0^\circ$	180°	179°	179°
	$\Phi=90^\circ$	164°	164°	162°

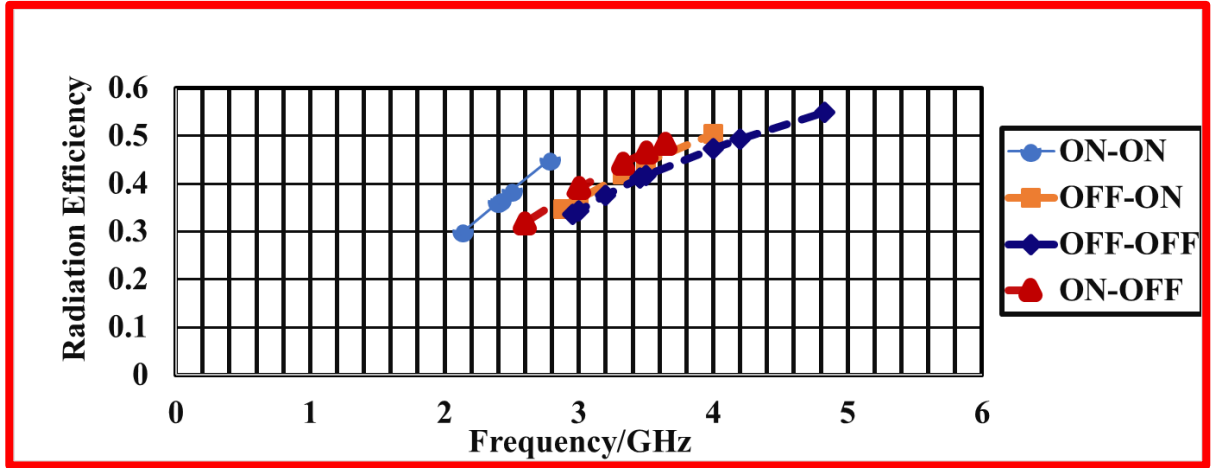
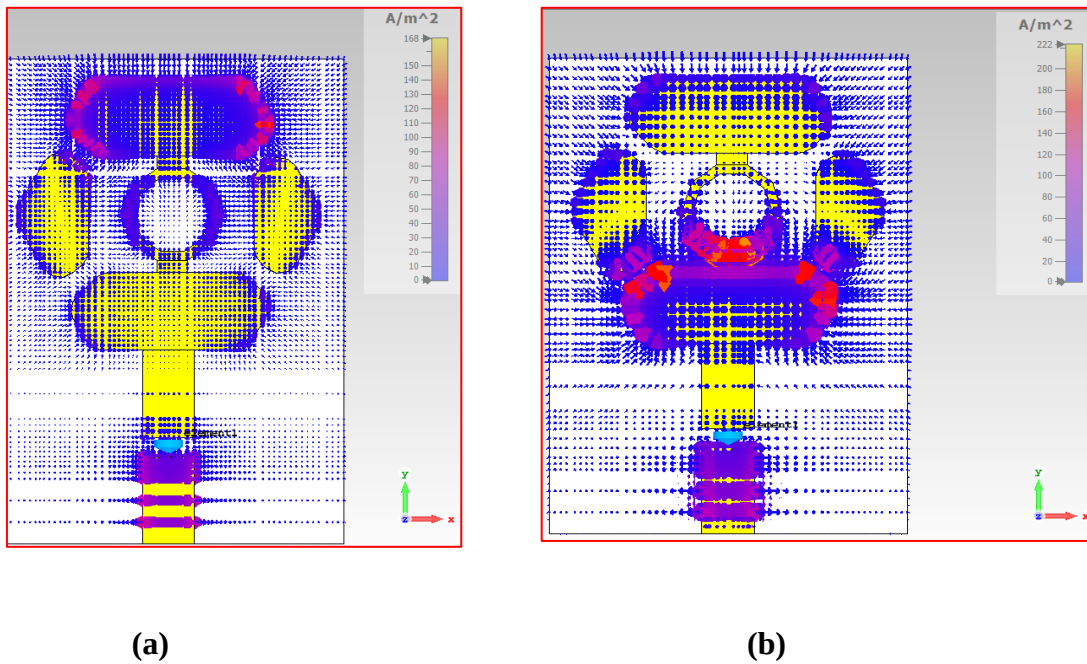


Figure 4.11. Radiation Efficiency of the proposed frequency reconfigurable antenna for each PIN diode state.

Confirming the electrical wavelength via surface current distribution analysis constitutes a pivotal stage in substantiating the resonance behavior of antennas, especially in designs involving frequency reconfigurability. The presentation of results for each state in Figure 4.12, which correspond to the anticipated electrical length, holds immense significance, particularly within the realm of sub-6 GHz applications.



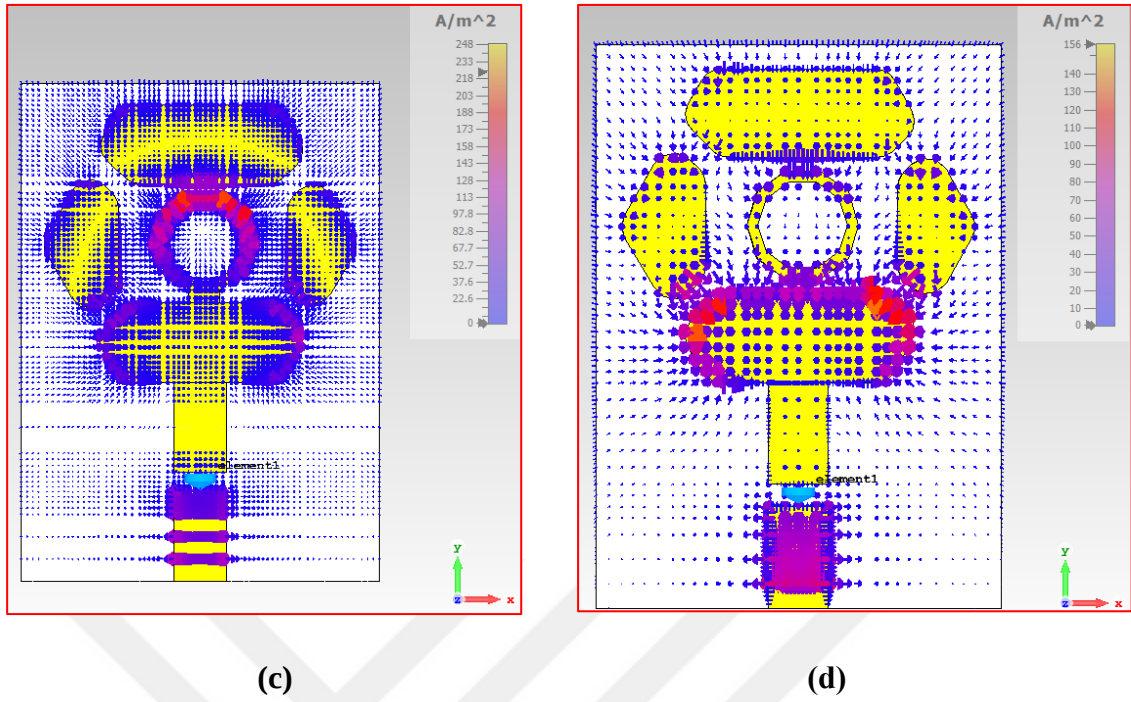


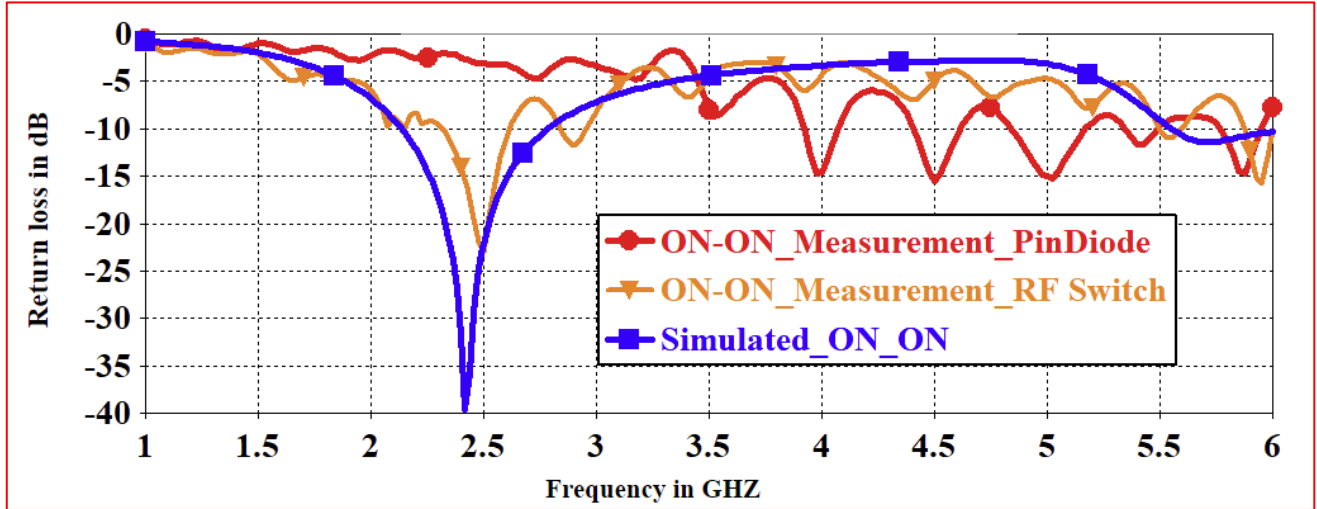
Figure 4.12. Surface current distribution of a) State-1 (ON-ON, 2.4 GHz), b) State-2 (OFF-ON, 3.27 GHz), c) State-3 (ON-OFF, 3 GHz), d) State-4 (OFF-OFF, 3.5 GHz).

4.3.2. Measurement Results

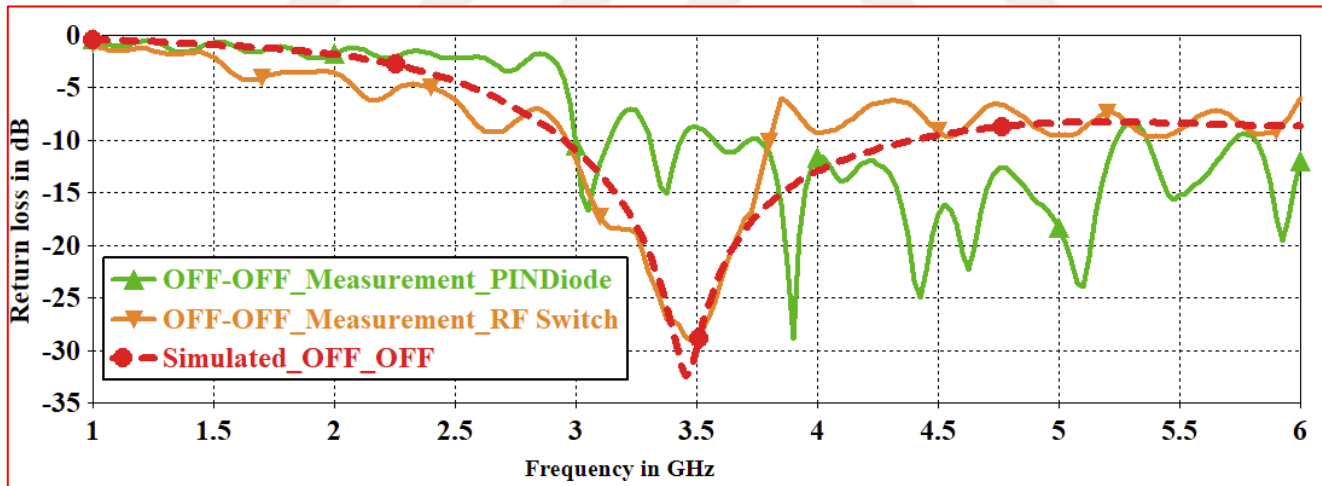
Figure 4.13 presents a comprehensive overview by showcasing the simulated and measured results for each state independently, scrutinizing the antenna's performance in conjunction with the two distinct switching mechanisms: PIN diode and SPDT. Notably, the configuration involving the PIN diode offers integration advantages. However, it is essential to acknowledge the drawbacks associated with electronic reconfigurability, such as nonlinearity effects, interference losses, and negative implications of biasing lines. The incorporation of DC biasing lines to accommodate PIN diodes introduces undesirable electromagnetic coupling, resulting in interference losses and a reduction in overall efficiency. The nonlinear behavior of PIN diodes under varying bias conditions further exacerbates signal distortion, ultimately deteriorating the desired system performance. These challenges underscore the intricate trade-offs that necessitate careful consideration when selecting between various reconfigurability approaches.

In comparison to SPDT switches, the adoption of PIN diodes for electronic reconfigurability introduces its own set of challenges, primarily attributed to the DC biasing prerequisites. Unlike SPDT switches, which can operate with minimal biasing, PIN diodes demand a

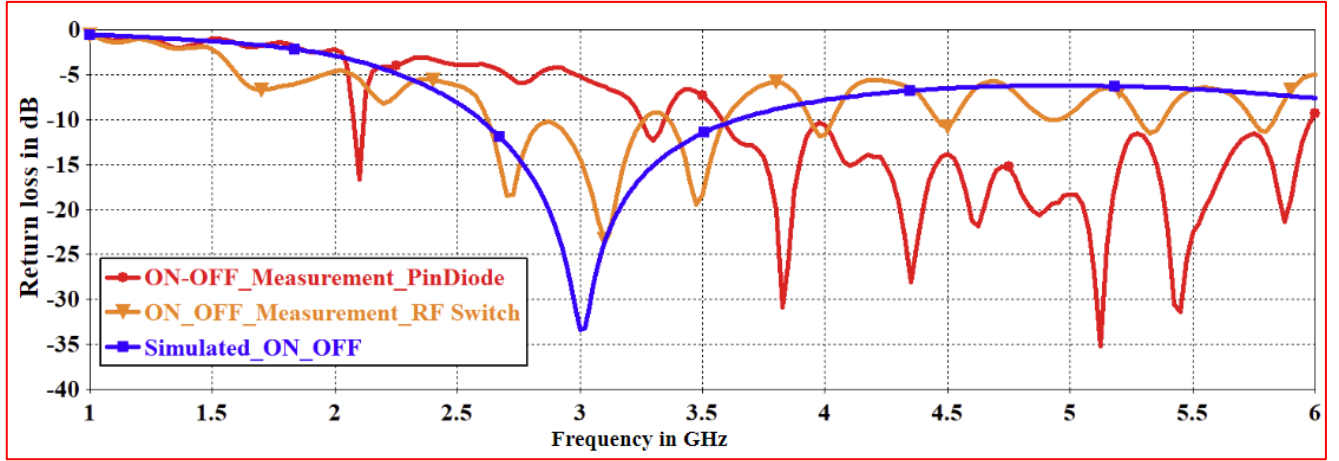
continuous DC bias current. It is worth concluding that this bias current not only consumes power but also triggers nonlinear effects, adversely influencing the holistic performance of the system.



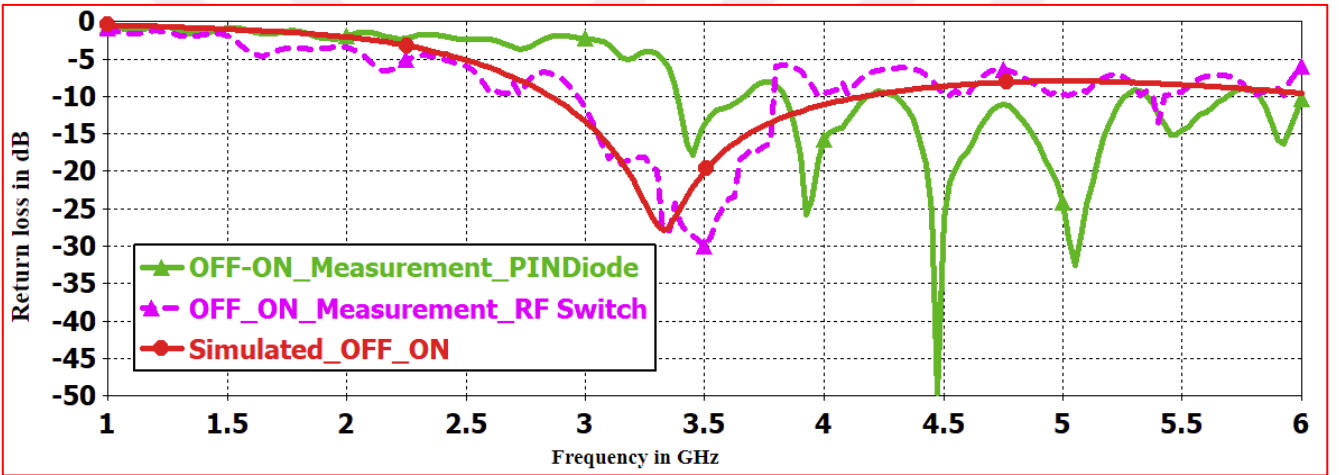
(a)



(b)



(c)



(d)

Figure 4.13. The comparison of the simulated and measured reflection coefficient (S_{11}) of the proposed frequency reconfigurable antenna for the state of a) ON-ON, b) OFF-OFF, c) ON-OFF, d) OFF-ON

Through the combined utilization of ring resonators and switches, the proposed antenna design establishes a mechanism for achieving frequency reconfigurability. By manipulating the switch states and adjusting the dimensions of the ring resonator, the antenna's resonant frequencies and bandwidths can be fine-tuned to align with diverse communication standards, frequency bands, and system specifications. This innovative approach represents a significant advancement in the realm of flexible and adaptable antennas for wireless communication systems. The integration of ring resonators, RF switches, redundancy in operating bands, and an omni-directional radiation pattern embodies the distinctive attributes of our design,

marking a substantial stride in addressing the requisites of contemporary communication landscapes. This enables the antenna to adeptly accommodate various operating conditions and optimize its performance across a spectrum of wireless communication applications. Table 4.3 underscores the originality of this antenna by contrasting it with other frequency reconfigurable antennas detailed in existing literature. The outcomes of this study hold substantial implications for practical applications and the potential enhancement of wireless communication across different environmental conditions. Primarily, the proposed frequency reconfigurable antenna designs, incorporating ring resonators and switches, offer augmented functionality, adaptability, and versatility within wireless communication systems. The ability to manipulate switch states and the presence of ring resonators empowers the antenna to tailor its resonant frequencies and bandwidths, effectively adapting to diverse communication standards, frequency bands, and system demands. Such adaptability is crucial for real-world scenarios where wireless communication systems operate within varying frequency bands and environments. Additionally, the study underscores the compactness and spatial efficiency inherent in the proposed designs, rendering them suitable for applications characterized by size constraints, as highlighted in Table 4.3. This characteristic holds particular importance in contexts where available physical space for antenna installation is limited, such as compact devices or urban settings. The integration of ring resonators adds an extra accuracy in frequency control, further improving the antenna's adaptability and performance optimization. This capability becomes especially relevant in scenarios involving challenging weather conditions. For instance, in adverse weather situations prone to signal interference or attenuation, the capacity to adjust resonant frequencies and bandwidths can effectively mitigate the influence of weather-related issues on wireless communication. Furthermore, the study demonstrates the antenna's capacity for radiation pattern reconfigurability across varying frequencies and angles. This capability can be harnessed to fine-tune the antenna's beamforming ability, a critical aspect for enhancing wireless communication in different weather conditions. By manipulating the radiation pattern, the antenna can concentrate transmitted or received signals in specific directions, thus enhancing signal strength and minimizing the impact of weather-related signal degradation. The findings of this study also usher in new prospects for optimizing antenna performance and addressing the intricacies linked to frequency reconfigurability within wireless communication systems. The proposed designs hold promise for future wireless communication technologies, with the potential to

ameliorate wireless communication across varying weather conditions by offering adaptability, compactness, and radiation pattern control.

Table 4.3. Comparison of the proposed antenna with the literature

Ref	Dimension (mm²)	Switching Element	Frequency Range
[229]	25x30	NA	2.34-5.5 GHz
[230]	100x100	PIN Diode (2)	2.2-5.5 GHz
[231]	14x36	PIN Diode (2)	2-6 GHz
[232]	25x27	PIN Diode (2)	2-6 GHz
[233]	50x45	PIN Diode (2)	2.5-5 GHz
[234]	30x30	PIN Diode (2)	1.8-4.5 GHz
[235]	33x16	PIN Diodes (3)	2-5.2 GHz
This work	25x18	PIN Diodes /RF switch (2) and ring resonator	2.3-4.83 GHz

5. SIMULATION AND MEASUREMENT OF NONLINEAR EFFECTS IN FREQUENCY-RECONFIGURABLE MICROSTRIP ANTENNAS WITH RESONATOR INTEGRATION AND SPDT SWITCHES

The proposed antenna structure has been developed using CST Microwave Studio (MWS), employing a Rogers 4003C substrate with a thickness of 1.508 mm and a relative permittivity of 3.55. To showcase the antenna design, Figure 5.1 presents both front and side views of the novel antenna, complete with integrated switches and DC block capacitors (100 pF). Notably, CST MWS does not have the capability to simulate nonlinear components such as PIN diodes. Therefore, copper paths are utilized as stand-ins for the actual switches to circumvent distortions stemming from the nonlinearity of the switches during simulations. To further illustrate the concept, Figure 5.2 displays the four configurations resulting from different copper paths connections. Altering the presence or absence of these paths directly affects the electrical length of the antenna. The dimensions of the antenna's ground plane consist of a length denoted as " a " measuring 10 mm and a width labeled as " b " measuring 10.5 mm. Through the integration of switches and the manipulation of the electrical length, the proposed design achieves frequency reconfigurability. By employing the copper plates substitution technique within CST MWS, nonlinear effects are accounted for, enabling the simulation and optimization of the reconfigurable antenna structure. Figure 5.2 further elucidates all four configurations, complete with dimensional labels to facilitate understanding of the electrical length associated with each state.

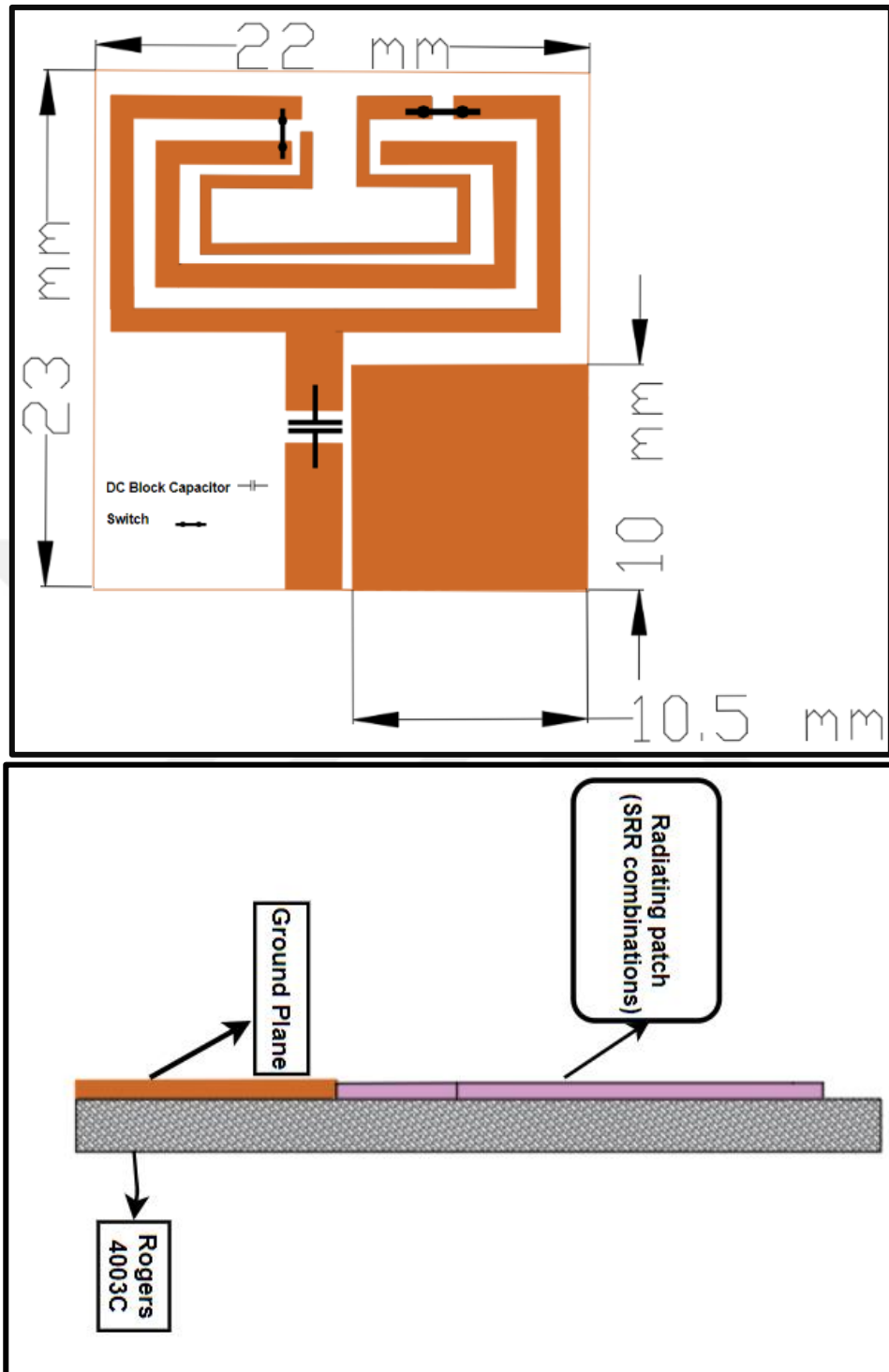


Figure 5.1. Proposed frequency reconfigurable antenna with front and side views

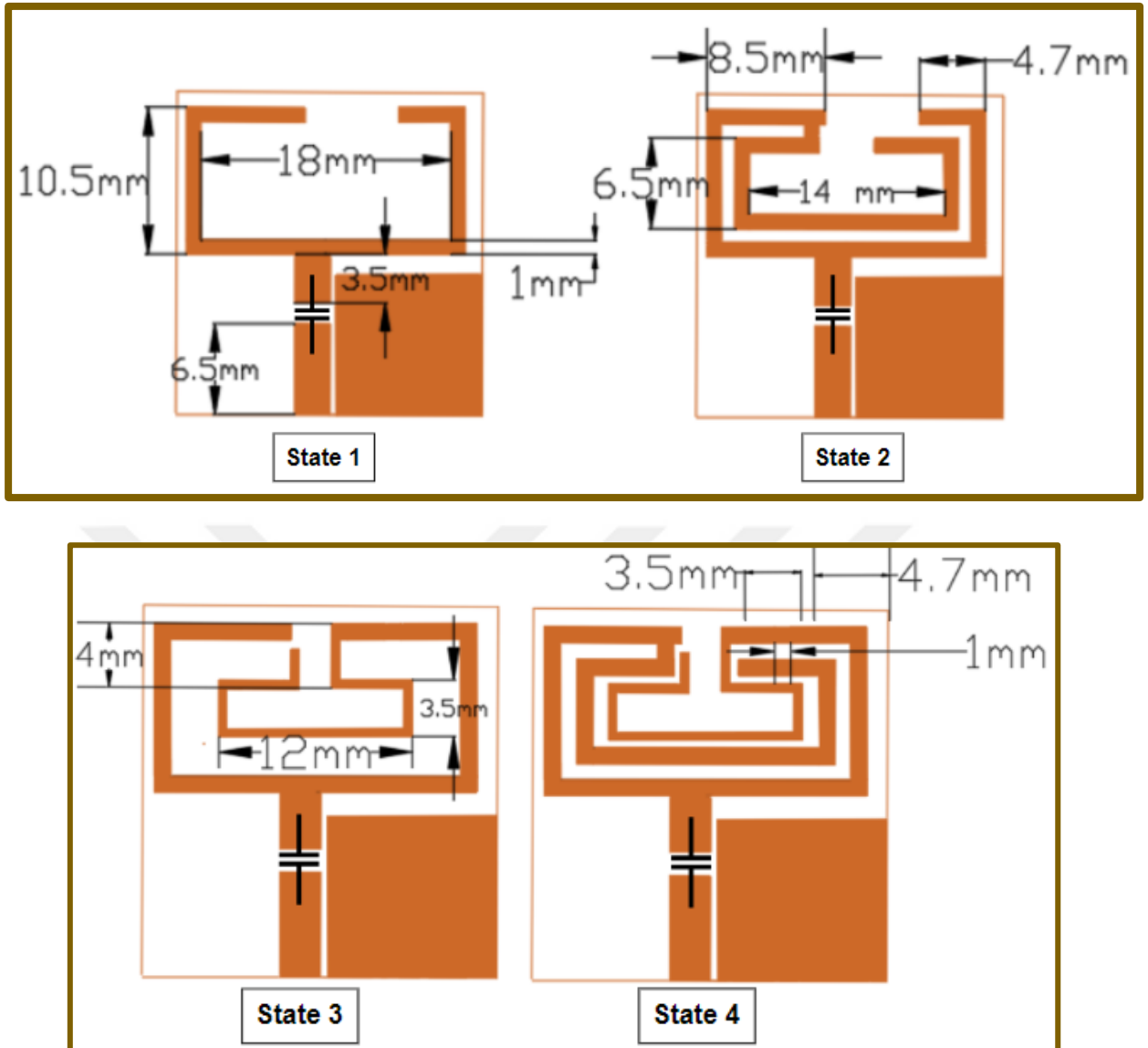


Figure 5.2. Four configurations of the novel proposed antenna structure with the absence and presence of the copper paths

The fabricated frequency reconfigurable antenna encompassing both copper paths and the BAR64-02V component is outlined in Figure 5.3. To emulate the presence of switches, copper paths are employed within the simulation framework, while also considering the nonlinearity inherent in the switches. This approach provides valuable insights into the antenna's performance, aiding in optimization and refinement. Subsequently, the fabrication process transforms the virtual designs into tangible prototypes. The physical realization of the antenna involves carefully adhering to the dimensions and specifications determined during the simulation phase. The integration of the BAR64-02V component, known for its capability

to provide reconfigurability, adds a practical dimension to the design. These fabricated prototypes serve as tangible representations of the antenna's functionality, enabling experimental validation of its anticipated behavior.



a)



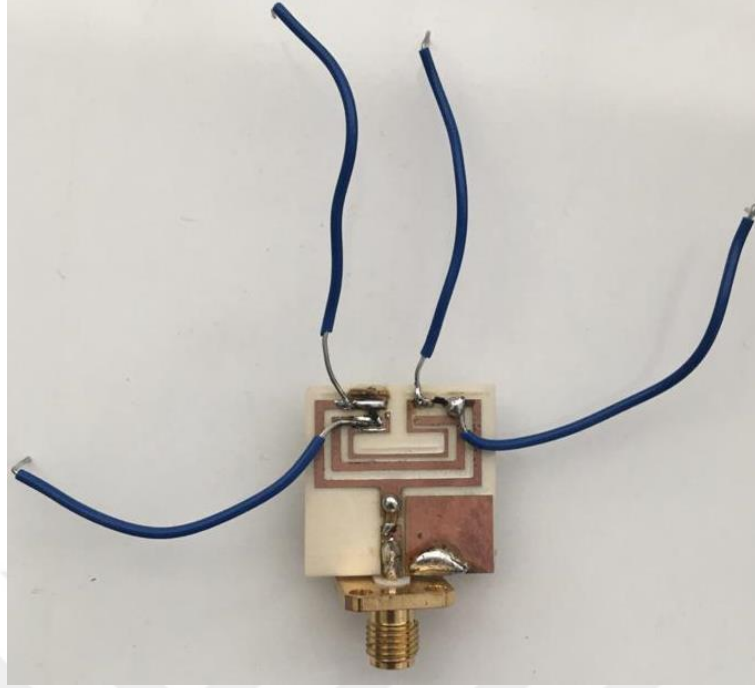
b)



c)



d)



e)

Figure 5.3. The proposed fabricated antenna structure a) State-1, b) State-2, c) State-3, d) State-4, and e) with BAR64-02V PIN diodes

5.1. Simulation Results

Figure 5.4 illustrates the reflection coefficients (S_{11}) of the proposed antenna structure. It is clear from Figure 5.4 that frequency agility occurs over the frequency range of sub-6 GHz by changing the PIN diode states. The operating frequency is from 4.14 GHz to 4.33 GHz when both PIN diodes are OFF. The proposed structure with ON-OFF state of PIN diodes simultaneously radiates two different operating frequency band including the resonance frequencies of 3.85 GHz and 5.17 GHz, respectively. Thirdly, in OFF-ON state of PIN diodes, the proposed structure radiates in dual band including the frequency range of 3.68-3.74 GHz with the resonance frequency of 3.7 GHz. The proposed structure with ON-ON state of PIN diodes allows to radiate from 3.39 GHz to 3.45 GHz at the resonance frequency of 3.42 GHz.

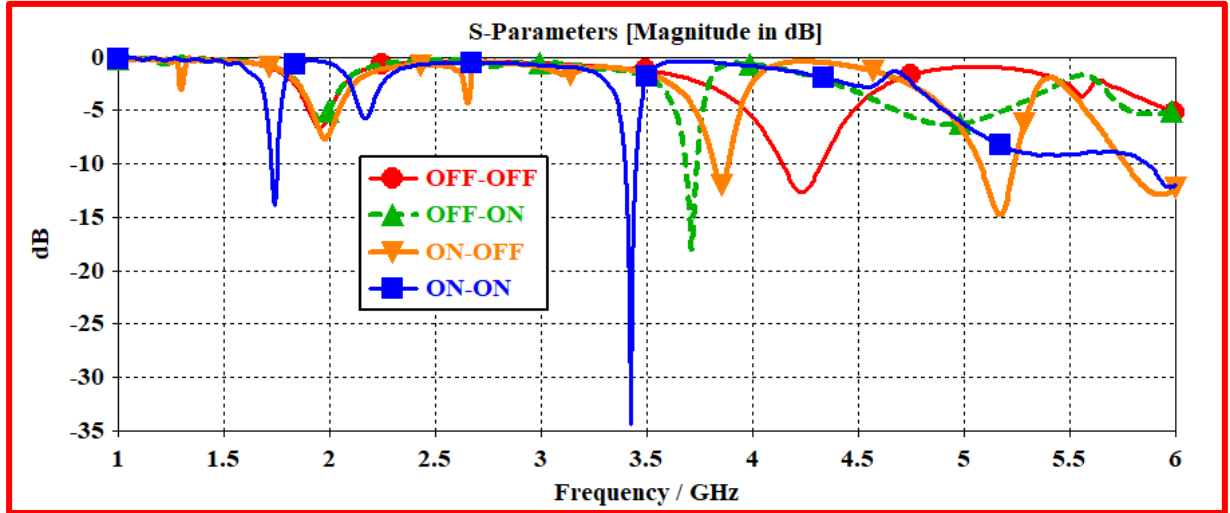
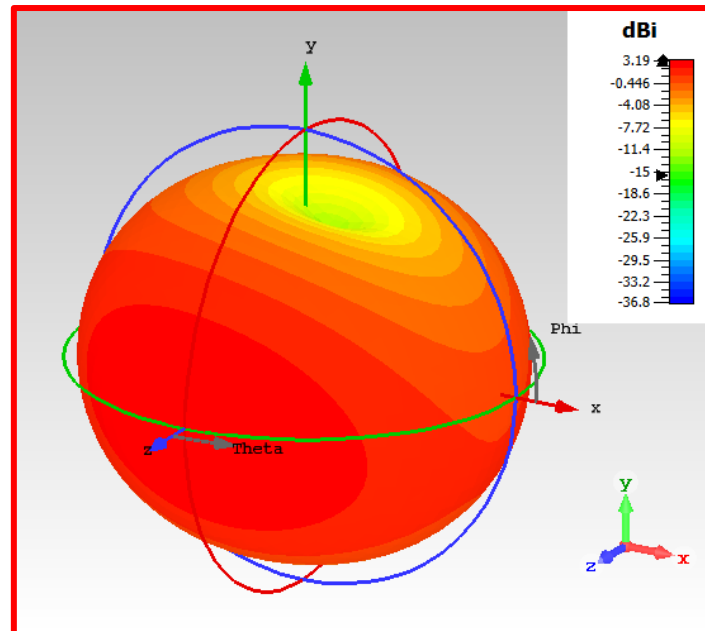
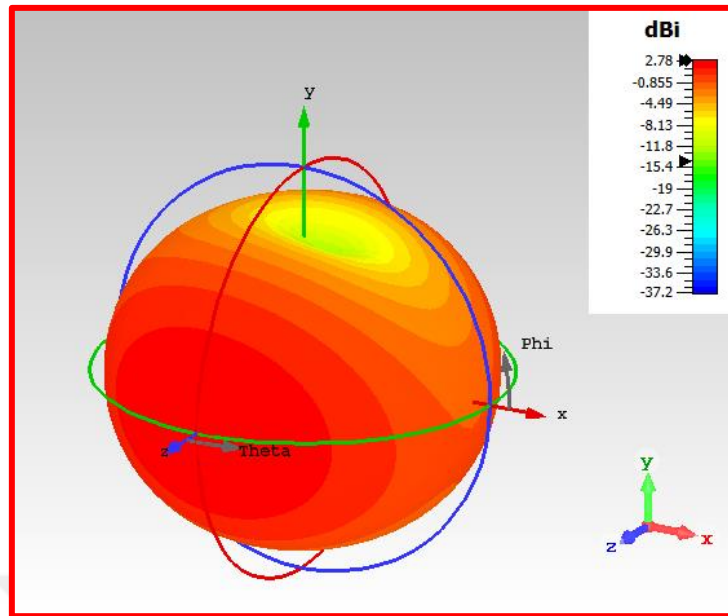


Figure 5.4. Reflection coefficients (S_{11}) of proposed frequency reconfigurable antenna

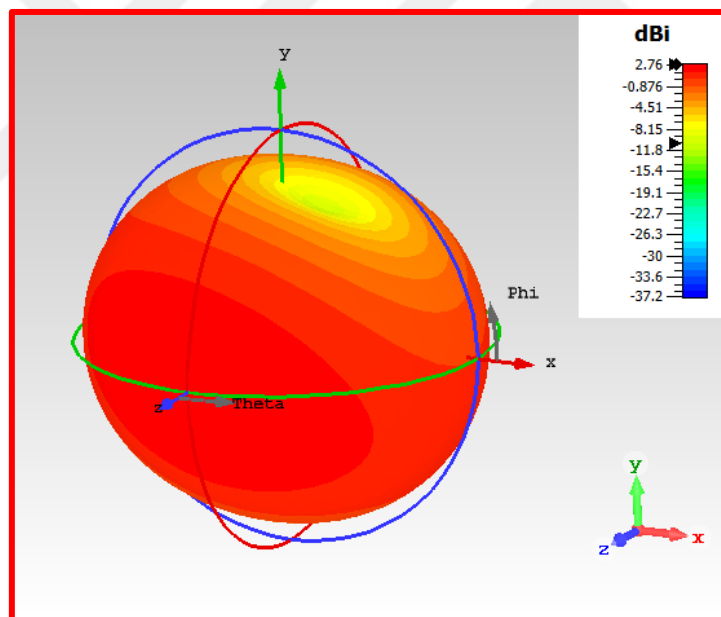
Radiation pattern characteristics are illustrated in Figure 5.5 in terms of each PIN diode state at corresponding resonance frequencies. It is deduced from Figure 5.5 that the proposed antenna structure has relatively omni-directional radiation pattern characteristics and acceptable performance with prominent gain values.

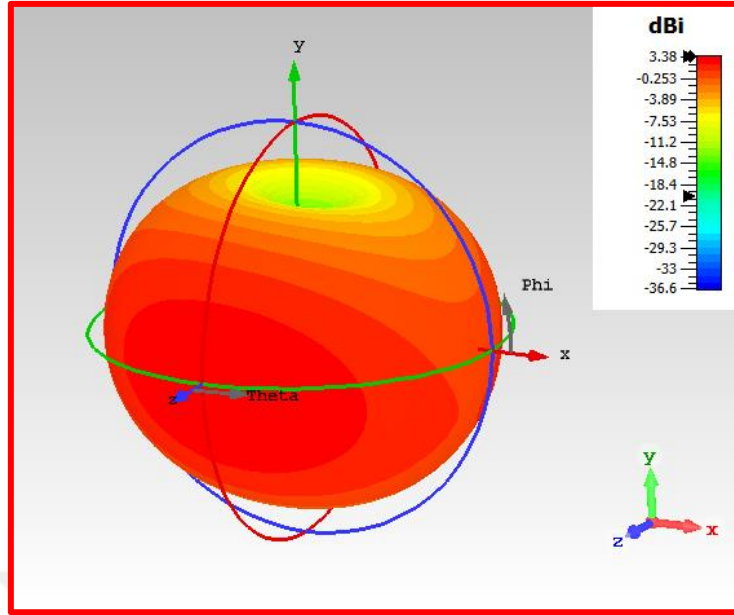


a) OFF-OFF state at the frequencies of 4.23 GHz

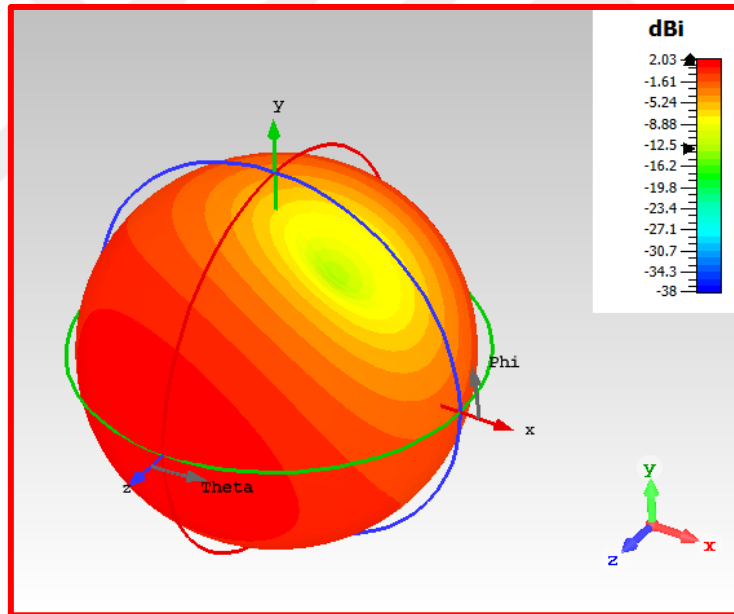


b) OFF-ON state at the frequencies of 3.7 GHz





c) ON-OFF state at the frequencies of 3.85 GHz, and 5.17 GHz



d) ON-ON state at the frequencies of 3.5 GHz

Figure 5.5. The radiation pattern characteristics of a) OFF-OFF state at 4.23 GHz b) OFF-ON state at 3.7 GHz c) ON-OFF state at 3.89 and 5.17 GHz, and d) ON-ON state at 3.42 GHz of the proposed frequency reconfigurable antenna

The bandwidths, with respect to -10 dB, are depicted in Table 5.1. Addition to these, radiation efficiency, max gain over frequency range of interest, and radiation pattern at different frequencies are investigated in order to carry out the suitability of the application field standards. All aforementioned antenna parameters are simulated and evaluated on account of entire Sub-6 GHz spectrum.

Table 5.1. RF performance parameters of frequency reconfigurable antenna for each diode state

States	Operating Frequency Range	Resonance Frequency	Gain
OFF&OFF	4.14-4.33 GHz	4.23 GHz	3.19 dBi
OFF&ON	3.68-3.74 GHz	3.7 GHz	2.78 dBi
ON&OFF	3.81-3.88 GHz	3.85 GHz	2.76 dBi
	5.07 -5.24 GHz	5.17 GHz	3.84 dBi
ON&ON	3.39-3.45 GHz	3.42 GHz	2.03 dBi

5.2. Measurement Results

To verify the simulation analysis, a prototype of the proposed antenna is fabricated and analyzed experimentally as illustrated in Figure 5.6. It is outlined from the figure that two pin diodes (BAR64-02V) are biased with the help of a DC voltage source (appx. 3.5 V). Biasing circuitry is also implemented as shown in Figure 5.6. The components are made up of four 13 μ H inductors, four 100 Ω resistors, and a DC Block Capacitor of 22 nF. DC block capacitor and biasing circuitry are used to eliminate interference between DC and RF signals and make a proper comparison between simulated and measured results. The measured reflection coefficients with PIN diodes concept are detailed in Figure 5.7. It is clear from Figure 5.7 that the simulation and measurement results are not in good agreement.

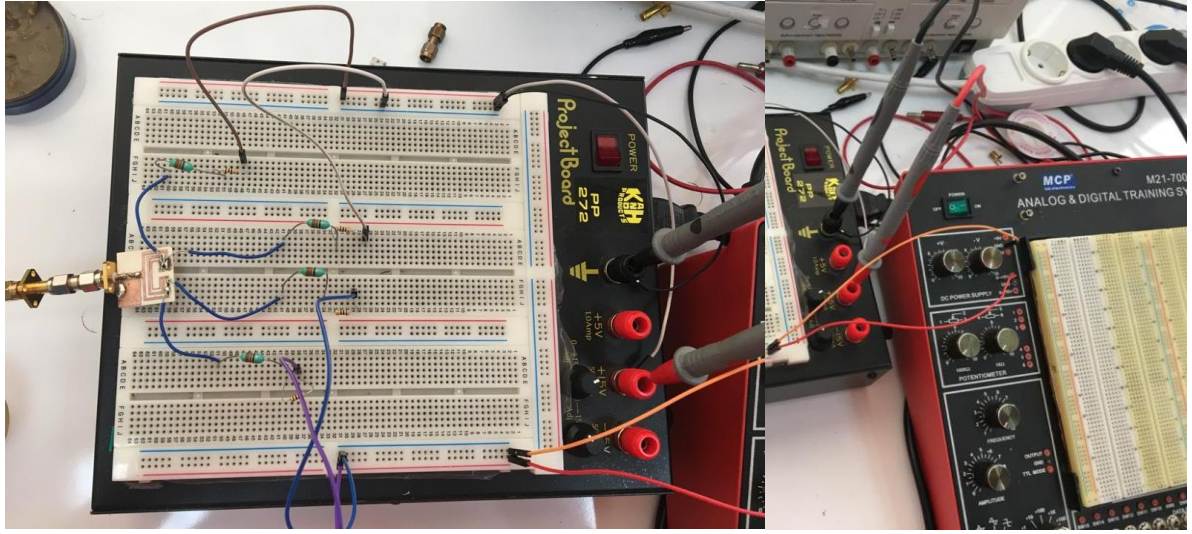


Figure 5.6. Measurement setup and overall biasing circuitry

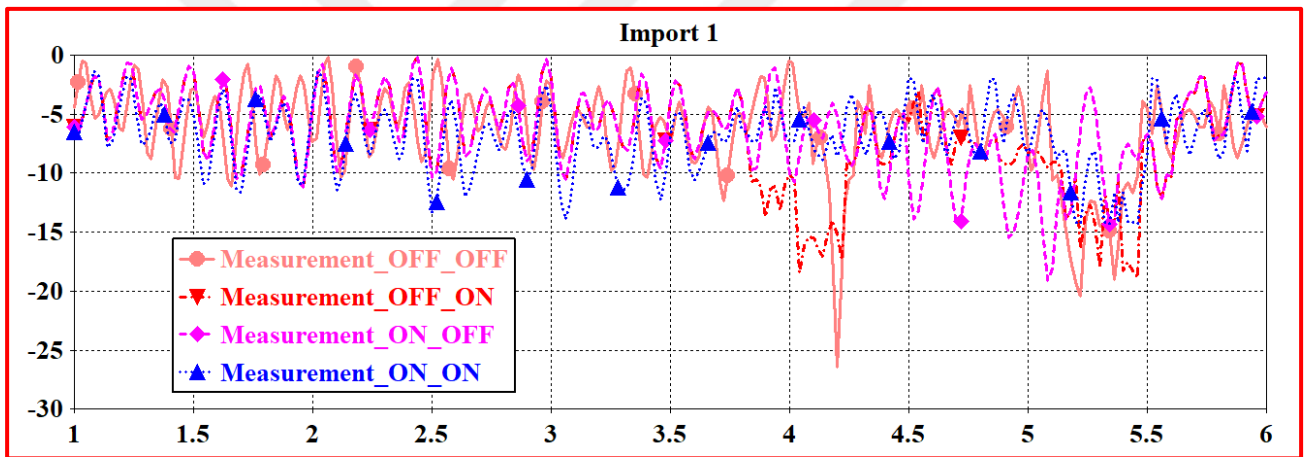


Figure 5.7. The measured return loss characteristics of the proposed antenna with PIN diode conditions

The results presented in Figure 5.8 provide a significant validation of the frequency-reconfigurable microstrip antenna design in the sub-6 GHz band, where each state is measured using only copper paths as substitutes for switches. This experimental comparison between measurement and simulation highlights the accuracy and reliability of the proposed antenna's performance predictions. The close agreement between the measurement and simulation results, as depicted in Figure 5.8, underscores the effectiveness of the copper path substitution technique in CST Microwave Studio for capturing the essential characteristics of the antenna's behavior. This agreement between measurements and simulations signifies that the model accurately represents the antenna's reconfigurable capabilities, despite the inherent

nonlinearities of the switching components (represented by copper paths) that CST MWS cannot directly simulate. Furthermore, the observation that the measurement results closely follow the simulation results underscores the robustness of the design. The key insight derived from the experimental analysis, which indicates that DC biasing circuitry and biasing wires have detrimental effects on antenna performance parameters, is of paramount importance. Addressing the negative impact of DC biasing circuitry and biasing wires on performance parameters becomes a crucial aspect when translating the design into practical applications. It may involve innovative circuitry designs or integration techniques that mitigate or compensate for these detrimental effects, ensuring consistent and reliable performance across different antenna states. In conclusion, the compatibility between measured and simulated results validates the effectiveness of the proposed frequency-reconfigurable microstrip antenna design in the sub-6 GHz band. Furthermore, the identified impact of DC biasing on performance underscores the need for careful consideration of biasing strategies during practical implementation. This study thus contributes to advancing the understanding and feasibility of frequency reconfigurable antennas in real-world communication systems operating within the sub-6 GHz frequency range.

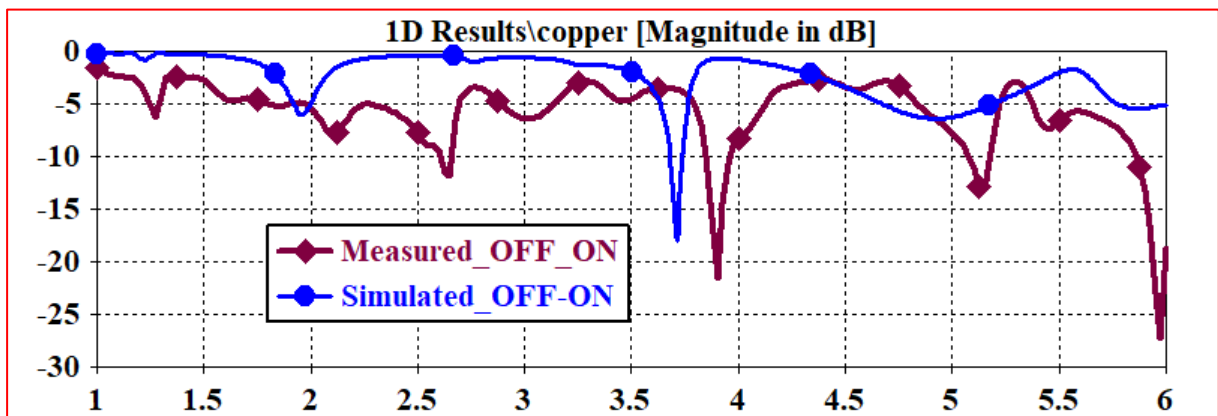
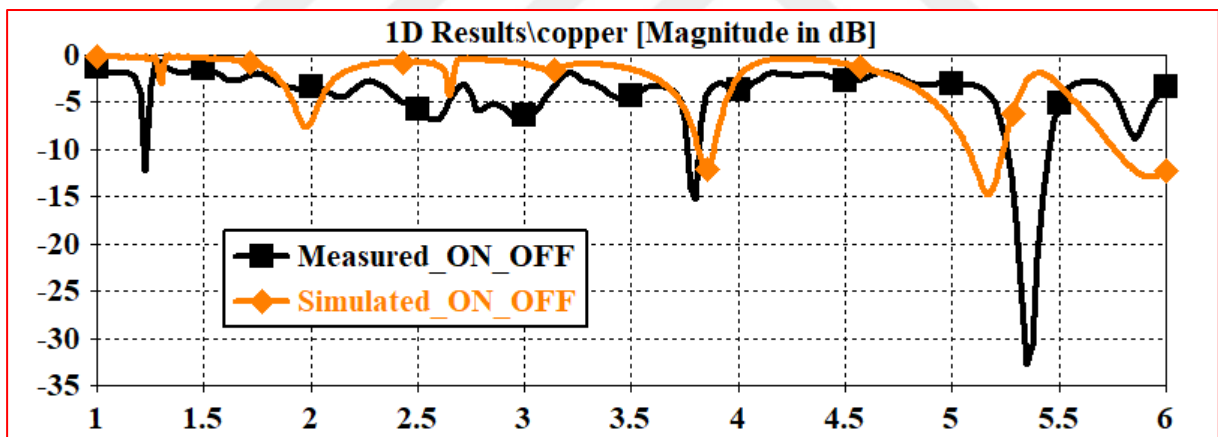
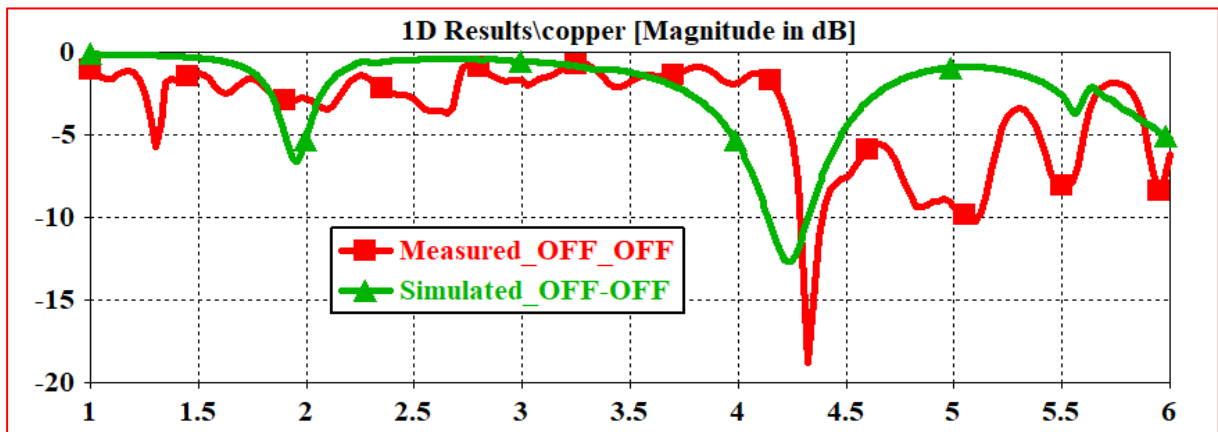
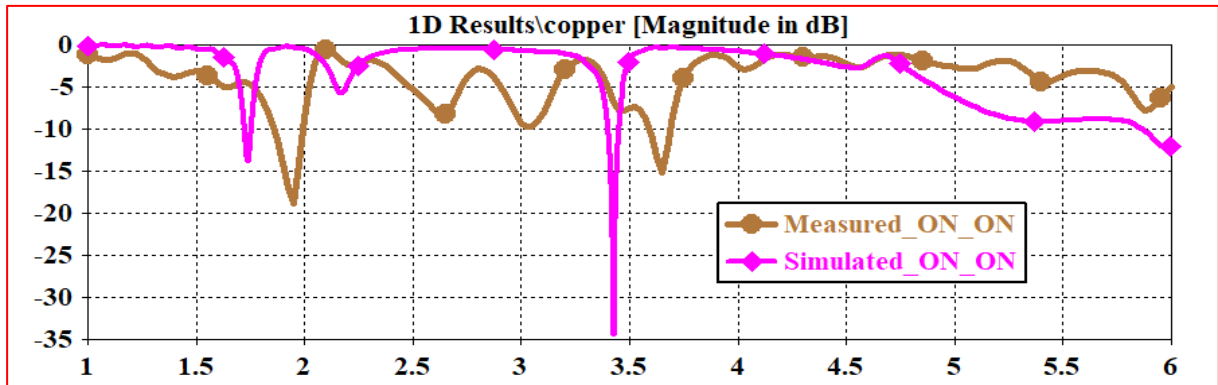


Figure 5.8. The measured return loss characteristics of the proposed antenna with copper path.

Table 5.2 depicts the comparisons of the proposed novel antenna structure with the other frequency reconfigurable antennas in the literature. It is clear from Table 5.2 that the proposed antenna almost overperforms the other frequency reconfigurable antenna in the literature in terms of compact size, number of operating frequency bands, low cost and unformidable design. It is noteworthy to mention that the proposed novel antenna can be integrated to many devices including access points, gateways, and smart phones in the sake of the tiny size.

Table 5.2. Performance comparison between proposed and reported frequency reconfigurable antennas in the frequency range of interest (sub-6 GHz Wireless Communication Systems)

Reference	Year	Dimension(mm ²)	Number of Operating Band	Gain (dBi)	Radiation Efficiency (%)
[241]	2014	40x35	3	1.92-3.02	76.4-86.5
[242]	2016	40x33	5	1.7-2.5	76.68
[243]	2016	40x35	3	1.48-3.26	84-93.5
[244]	2016	59x31	3	>3dBi	NA
[245]	2017	53x35	3	1.7-3.4	85-90
[246]	2017	40x22	4	1.72-2.96	76.4-92
[247]	2017	39x37	3	1.27-3.8	>90
[248]	2018	40x35	6	1.92-3.8	92.5-97
[249]	2019	60x60	5	1.31-2.77	-
[235]	2020	48.9x38.36	3	1.76-3.98	37.2-52.7
[250]	2020	33x16	8	1.85-3.46	NA
[251]	2021	40x32	9	1.25-3.6	70-84
[252]	2021	30x20	7	1.2-2.5	70-84
This Work	2023	23x22	6	2.43-4.78	86-98.6

6. CONCLUSION

This doctoral thesis presents the design of metamaterial-inspired antennas for IoT/5G applications in wireless communication systems. Integrating metamaterial structures into antenna design, the study leads to innovative approaches that remarkably improve the overall system performance.

This study makes a significant contribution to the literature by introducing novel antennas with resonator and switching element combinations for IoT/5G applications. The main focus of this work is the integration of resonators, PIN diodes and SPDT (Single-Pole Double-Throw) switches into the design of antenna structures. This combination provides the ability for dynamic adaptation and reconfiguration, allowing the antenna structure to adjust its radiation characteristics according to system requirements. The resonators, which are designed based on the principles of metamaterial structures, provide the intended frequency ranges and improved radiation performance. The PIN diodes and SPDT switches achieve control capability, allowing the antennas to change their states according to the needs of IoT/5G applications.

In the study, the proposed antennas with resonator-SPDT switch and resonator-PIN diode combinations are analysed both numerically and experimentally for each switch state condition namely ON-ON, ON-OFF, OFF-ON, OFF-OFF. According to the analysis results, the designed antennas exhibit versatility and ability to switch between different operational frequency bands.

The first frequency reconfigurable antenna structure proposed for sub-6 GHz applications is presented in Chapter 3. This antenna consists of outer split-ring resonators and inner spiral resonators with PIN diodes or SPDT switches. Return Loss, Radiation Pattern, and Radiation Efficiency are analysed in the sub-6 GHz range. Simulation results are confirmed by experimental analysis. Both simulation and measurement results show that antenna has a good performance in terms of compactness, wide operating band, and cost-effectiveness. The antenna's operational bandwidth together with its omnidirectional radiation pattern, makes it a good candidate for various applications in wireless communication systems.

Chapter 4 presents another frequency reconfigurable antenna design by integrating add-drop ring resonator with PIN diodes and RF switches. The different antenna states yield distinct

resonance frequencies and operating bands. Return Loss, Radiation Pattern, Radiation Efficiency and Current Distribution are investigated for all antenna states. According to obtained results, it is concluded that the proposed antenna is an attractive choice for applications such as Wi-Fi, Bluetooth, IoT, and mid-band 5G.

Another frequency-reconfigurable microstrip antenna operating in the sub-6 GHz band is analysed Chapter 5. PIN diodes, regulated by a DC voltage source, allow dynamic tuning of the antenna's resonant frequency. The use of DC block capacitors and biasing circuitry enables precise comparisons between simulation and measurement results. The results show good agreement even in the presence of non-linear switching components.

In conclusion, the innovative antenna designs, control mechanisms and reconfigurability features presented in this thesis make a significant contribution to wireless communication systems. These contributions play an important role in the design of frequency reconfigurable antennas and their use in IoT and 5G communication technologies. Additionally, the thesis offers a promising solution to the challenges in the Internet of Things and 5G communication systems by designing metamaterial inspired antennas.

7. SUGGESTIONS AND FUTURE WORKS

Based on the findings and conclusions of this PhD thesis, future research and studies on reconfigurable antenna design can make significant contributions to antenna design for wireless communications. These contributions enable the development of more compact, high-performance antennas and allow the fabrication of more efficient and adaptable devices for IoT and 5G applications.

Investigating machine learning algorithms and applying optimization techniques can lead to more effective antennas in terms of frequency and pattern reconfigurability. Additionally, antenna performance can be improved by further working on reconfiguration techniques for multi-band and wideband applications. Examining novel methods for the integration of metamaterial-inspired antennas into compact devices can also make a significant contribution to the studies about IoT and 5G systems.

REFERENCES

1. Patil, C., Karhe, R. and Aher, M., 2012. Review on generations in mobile cellular technology. *International Journal of Emerging Technology and Advanced Engineering*, 2(10), 901-912.
2. Arnold, C.C., 2015. Design, fabrication, and measurement of a multiple-input multiple-output (mimo) antenna for mobile communication
3. Arshad, Q.K.U.D., Kashif, A.U. and Quershi, I.M., 2019. A review on the evolution of cellular technologies. In 2019 16th International Bhurban Conference on Applied Sciences and Technology (IBCAST). IEEE: pp: 989-993.
4. Bhalla, M.R. and Bhalla, A.V., 2010. Generations of mobile wireless technology: A survey. *International Journal of Computer Applications*, 5(4), 26-32.
5. Matalgah, M.M. and Hammouri, O.M., 2007. International mobile telecommunications-2000 and 3G wireless systems. *Handbook of Computer Networks: LANs, MANs, WANs, the Internet, and Global, Cellular, and Wireless Networks*, 2, 716-750.
6. Cihangir, A. (2014). Antenna designs using matching circuits for 4G communicating devices (Doctoral dissertation, Université Nice Sophia Antipolis).
7. Chettri, L. and Bera, R., 2019. A comprehensive survey on internet of things (iot) towards 5G wireless systems. *IEEE Internet of Things Journal*.
8. Akpakwu, G.A., Silva, B.J., Hancke, G.P. and Abu-Mahfouz, A.M., 2017. A survey on 5G networks for the internet of things: Communication technologies and challenges. *IEEE Access*, 6, 3619-3647.
9. Popoola, S.I., Faruk, N., Atayero, A.A., Oshin, M.A., Bello, O.W. and Adigun, M., 2017. 5G radio access network technologies: Research advances. In *Proceedings of the World Congress on Engineering and Computer Science*, San Francisco. pp: 101-105.
10. Dragičević, T., Siano, P. and Prabakaran, S., 2019. Future generation 5G wireless networks for smart grid: A comprehensive review. *Energies*, 12(11), 2140.
11. Wortmann, F. and Flüchter, K., 2015. Internet of things. *Business & Information Systems Engineering*, 57(3), 221-224.
12. Al-Falahy, N. and Alani, O.Y., 2017. Supporting massive m2m traffic in the internet of things using millimeter wave 5G network. In 2017 9th Computer Science and Electronic Engineering (CEECE). IEEE: pp: 83-88.
13. ITU-R. 2015. "IMT Vision - Framework and Overall Objectives of the Future
14. Development of IMT for 2020 and Beyond." Recommendation ITU-R M.2083-0:1–21.
15. ITU-R. 2017. "Guidelines for Evaluation of Radio Interface Technologies for IMT2020." Report ITU-R M.2412-0: 1–144.

16. Dixit, A. S., Shevada, L. K., Raut, H. D., Malekar, R. R., and Kumar, S. (2020). Fifth generation antennas: a bibliometric survey and future research directions. *Library Philosophy and Practice*, 2020, 1-24.
17. Kim, Y., Kim, Y., Oh, J., Ji, H., Yeo, J., Choi, S., and Lee, J. (2019). New radio (NR) and its evolution toward 5G-advanced. *IEEE Wireless Communications*, 26(3), 2-7.
18. Langtry, C. (2016, December). ITU-R activities on 5G. In *IEEE World Forum on the Internet of Things* (pp. 14-16).
19. M. Marcus, "Spectrum Policy Issues for Millimeter Wave Mobile Communications", *IEEE Wireless Commun.*, vol. 21, no. 6, pp. 8-9, 2014.
20. Marcus, M. J. (2019). ITU WRC-19 spectrum policy results. *IEEE Wireless Communications*, 26(6), 4-5.
21. Lee, J., Tejedor, E., Ranta-aho, K., Wang, H., Lee, K. T., Semaan, E., and Jung, S. (2018). Spectrum for 5G: Global status, challenges, and enabling technologies. *IEEE Communications Magazine*, 56(3), 12-18.
22. LEI, W., Soong, A. C., Jianghua, L., Yong, W., Classon, B., Xiao, W., and Saboorian, T. (2021). *5G system design*. Cham: Springer International Publishing.
23. GSM Association. (2016). 5G spectrum-public policy position. GSM Assoc., London, UK, Tech. Rep.
24. Pujol, F., Manero, C. and Jaffal, T., 2019. 5G Observatory Quarterly Report 4. 4, 1-85. [Online]. Available at <http://5gobservatory.eu/wp-content/uploads/2019/07/80082-5G-Observatory-Quarterly-report-4-min.pdf>.
25. Feng, L., Hu, R.Q., Wang, J., Xu, P. and Qian, Y., 2016. Applying vlc in 5G networks: Architectures and key technologies. *IEEE Network*, 30(6), 77-83.
26. López, D.R., 2013. Reconfigurable pixel antennas for communications. Universitat Politècnica de Catalunya (UPC).
27. Ziolkowski, R.W., 2014. Metamaterial-based source and scattering enhancements: from microwave to optical frequencies. *Opto-Electron. Rev.* 14, 167–177. <https://doi.org/10.2478/s11772-006-0022-0>
28. Chen, Z., Guo, B., Yang, Y., and Cheng, C. (2014). Metamaterials-based enhanced energy harvesting: A review. *Physica B: Condensed Matter*, 438, 1-8.
29. Govindaraman, Loganathan; Arjunan, Arun; Baroutaji, Ahmad; Robinson, John; Olabi, Abdul-Ghani. (2021). Metamaterials for Energy Harvesting. 10.1016/B978-0-12-815732-9.00127-3.
30. Fan, Guohua, Sun, Kai, Hou, Qing, Wang, Zhongyang, Liu, Yao and Fan, Runhua. (2021). Epsilon-negative media from the viewpoint of materials science. *EPJ Applied Metamaterials*. 8. 11. 10.1051/epjam/2021005.

31. Carvalho, C. A. A. d. (2016). Relativistic electron gas: a candidate for nature's left-handed materials. *Physical Review D*, 93(10). <https://doi.org/10.1103/physrevd.93.105005>
32. Mederos-Henry, Francisco. (2019). Decoration of nanocarbon supports with magnetic nanoparticles for the control of electromagnetic propagation. 10.13140/RG.2.2.11712.89601.
33. Bose, J. C. (1898). On the rotation of plane of polarisation of electric wave by a twisted structure. *Proceedings of the Royal Society of London*, 63(389-400), 146-152.
34. Lindell, I. V., Sihvola, A. H., and Kurkijarvi, J. (1992). Karl F. Lindman: The last Hertzian, and a harbinger of electromagnetic chirality. *IEEE Antennas and Propagation Magazine*, 34(3), 24-30.
35. Veselago, V. G. (1967). Electrodynamics of substances with simultaneously negative and. *Usp. Fiz. Nauk*, 92, 517.
36. Pendry, J. B., Holden, A. J., Stewart, W. J., and Youngs, I. (1996). Extremely low frequency plasmons in metallic mesostructures. *Physical review letters*, 76(25), 4773.
37. Pendry, J. B., Holden, A. J., Robbins, D. J., and Stewart, W. J. (1998). Low frequency plasmons in thin-wire structures. *Journal of Physics: Condensed Matter*, 10(22), 4785.
38. Pendry, J. B., Holden, A. J., Robbins, D. J., and Stewart, W. J. (1999). Magnetism from conductors and enhanced nonlinear phenomena. *IEEE transactions on microwave theory and techniques*, 47(11), 2075-2084.
39. Pendry, J. B. (2000). Negative refraction makes a perfect lens. *Physical review letters*, 85(18), 3966.
40. Shelby, R. A., Smith, D. R., and Schultz, S. (2001). Experimental verification of a negative index of refraction. *Science*, 292(5514), 77-79.
41. Ziolkowski, R. W. (2001). Superluminal transmission of information through an electromagnetic metamaterial. *Physical Review E*, 63(4), 046604.
42. Ziolkowski, R. W., and Heyman, E. (2001). Wave propagation in media having negative permittivity and permeability. *Physical review E*, 64(5), 056625.
43. Zhi-ning, C. H. E. N. (2014). Metamaterials and metamaterial-based antenna technology. *上海大学学报 (自然科学版)*, (2014 年 05), 531-540.
44. Ali, T., and Biradar, R. C. (2017). A compact multiband antenna using $\lambda/4$ rectangular stub loaded with metamaterial for IEEE 802.11 N and IEEE 802.16 E. *Microwave and Optical Technology Letters*, 59(5), 1000-1006.
45. Kulkarni, N., and Lohiya, G. (2016). A Compact Microstrip Patch Antenna using Metamaterial. *International Journal of Engineering Trends and Technology*, 42(7), 365-369.
46. Ripin, N., Saidy, W. M. A. W., Sulaiman, A. A., Rashid, N. E. A., and Hussin, M. F. (2013, December). Miniaturization of microstrip patch antenna through metamaterial

- approach. In 2013 IEEE Student Conference on Research and Development (pp. 365-369). IEEE.
47. Lou, R. K. M., Aribi, T., and Ghobadi, C. (2010, December). Improvement of characteristics of microstrip antenna using of metamaterial superstrate. In *Proc. International Conf. on Communications Engineering* (pp. 22-24).
 48. Huang, H., Liu, Y., Zhang, S., and Gong, S. (2014). Multiband metamaterial-loaded monopole antenna for WLAN/WiMAX applications. *IEEE antennas and wireless propagation letters*, 14, 662-665.
 49. Gangwar, D., Das, S., and Yadava, R. L. (2013, December). Multiband microstrip stacked patch antenna using CSRR. In 2013 International Conference on Microwave and Photonics (ICMAP) (pp. 1-4). IEEE.
 50. Chen, Z. N., Qing, X., Shi, J., and Liu, W. (2015, December). Metamaterial-based antennas: Engineering designs. In 2015 Asia-Pacific Microwave Conference (APMC) (Vol. 1, pp. 1-3). IEEE.
 51. Kumar, V., and Wu, Y. (2018). Metamaterial Based Circular Disc Patch Antenna Miniaturization. *Advanced Electromagnetics*, 7(5), 137-144.
 52. Erentok, A., and Ziolkowski, R. W. (2008). A summary of recent developments on metamaterial-based and metamaterial-inspired efficient electrically small antennas. *Turkish Journal of Electrical Engineering & Computer Sciences*, 16(1), 21-32.
 53. Tamrakar, M., and Usha Kiran, K. (2019). Bandwidth enhancing method using tri-ring resonator metamaterial for small devices. *Microwave and Optical Technology Letters*, 61(4), 886-890.
 54. Fang, N., Lee, H., Sun, C., and Zhang, X. (2005). Sub-diffraction-limited optical imaging with a silver superlens. *Science*, 308(5721), 534-537.
 55. Landy, N. I., Sajuyigbe, S., Mock, J. J., Smith, D. R., and Padilla, W. J. (2008). Perfect metamaterial absorber. *Physical review letters*, 100(20), 207402.
 56. Zhang, X., and Liu, Z. (2008). Superlenses to overcome the diffraction limit. *Nature materials*, 7(6), 435.
 57. Chen, H., Chan, C. T., and Sheng, P. (2010). Transformation optics and metamaterials. *Nature materials*, 9(5), 387.
 58. Houck, A. A., Brock, J. B., and Chuang, I. L. (2003). Experimental observations of a left-handed material that obeys Snell's law. *Physical Review Letters*, 90(13), 137401.
 59. Landy, N. I., Bingham, C. M., Tyler, T., Jokerst, N., Smith, D. R., and Padilla, W. J. (2009). Design, theory, and measurement of a polarization-insensitive absorber for terahertz imaging. *Physical review B*, 79(12), 125104.
 60. Liu, Y., and Zhang, X. (2011). Metamaterials: a new frontier of science and technology. *Chemical Society Reviews*, 40(5), 2494-2507.

61. Ding, F., Cui, Y., Ge, X., Jin, Y., and He, S. (2012). Ultra-broadband microwave metamaterial absorber. *Applied physics letters*, 100(10), 103506.
62. Metz, C. (2005). U.S. Patent No. 6,958,729. Washington, DC: U.S. Patent and Trademark Office.
63. Ramakrishna, S. A., Pendry, J. B., Wiltshire, M. C. K., and Stewart, W. J. (2003). Imaging the near field. *Journal of Modern Optics*, 50(9), 1419-1430.
64. Shadrivov, I. V., Sukhorukov, A. A., Kivshar, Y. S., Zharov, A. A., Boardman, A. D., and Egan, P. (2004). Nonlinear surface waves in left-handed materials. *Physical Review E*, 69(1), 016617.
65. Guo, C. F., Sun, T., Cao, F., Liu, Q., and Ren, Z. (2014). Metallic nanostructures for light trapping in energy-harvesting devices. *Light: Science & Applications*, 3(4), e161.
66. Lee, J. B., Peng, S., Yang, D., Roh, Y. H., Funabashi, H., Park, N., and Luo, D. (2012). A mechanical metamaterial made from a DNA hydrogel. *Nature Nanotechnology*, 7(12), 816.
67. Simovski, C. R., Belov, P. A., Atrashchenko, A. V., and Kivshar, Y. S. (2012). Wire metamaterials: physics and applications. *Advanced Materials*, 24(31), 4229-4248.
68. Silveirinha, M. G., Alù, A., and Engheta, N. (2007). Parallel-plate metamaterials for cloaking structures. *Physical Review E*, 75(3), 036603.
69. Pendry, J. B. (2003). Perfect cylindrical lenses. *Optics Express*, 11(7), 755-760.
70. Araujo, H. X., Bolzan, E., Casella, I. R. S., Capovilla, C. E., and Kretly, L. C. (2014, September). Metamaterial-based antenna for RFID applications. In 2014 IEEE Brasil RFID (pp. 1-3). IEEE.
71. Karaaslan, M., Bağmancı, M., Ünal, E., Akgol, O., and Sabah, C. (2017). Microwave energy harvesting based on metamaterial absorbers with multi-layered square split rings for wireless communications. *Optics Communications*, 392, 31-38.
72. Hasan, M., Rahman, M., Faruque, M. R. I., Islam, M. T., and Khandaker, M. U. (2019). Electrically Compact SRR-Loaded Metamaterial Inspired Quad Band Antenna for Bluetooth/WiFi/WLAN/WiMAX System. *Electronics*, 8(7), 790.
73. Tütüncü, B., Torpi, H., and Urul, B. (2018). A comparative study on different types of metamaterials for enhancement of microstrip patch antenna directivity at the Ku-band (12 GHz). *Turkish Journal of Electrical Engineering & Computer Sciences*, 26(3), 1171-1179.
74. Rajalakshmi, P., and Gunavathi, N. (2018). Gain enhancement of cross shaped patch antenna for IEEE 802.11/ax Wi-Fi applications. *Progress In Electromagnetics Research*, 80, 91-99.
75. Elwi, T. A. (2018). Metamaterial based a printed monopole antenna for sensing applications. *International Journal of RF and Microwave Computer-Aided Engineering*, 28(7), e21470.

76. Roy, S., and Chakraborty, U. (2019). Metamaterial Based Dual Wideband Wearable Antenna for Wireless Applications. *Wireless Personal Communications*, 106(3), 1117-1133.
77. Gao, B., Yuen, M. M., and Ye, T. T. (2017). Flexible frequency selective metamaterials for microwave applications. *Scientific Reports*, 7, 45108.
78. Karakaya, E., Mülazımoğlu, C., Can, S., Yılmaz, A. E., and Akaoğlu, B. (2016, May). Metamaterial design for energy harvesting applications. In 2016 24th Signal Processing and Communication Application Conference (SIU) (pp. 509-512). IEEE.
79. Wu, B. I., Wang, W., Pacheco, J., Chen, X., Grzegorzczuk, T. M., and Kong, J. A. (2005). A study of using metamaterials as antenna substrate to enhance gain. *Progress In Electromagnetics Research*, 51, 295-328.
80. Islam, M., Islam, M., Samsuzzaman, M., Faruque, M., Misran, N., Pola, and Mansor, M. (2015). A miniaturized antenna with negative index metamaterial based on modified SRR and CLS unit cell for UWB microwave imaging applications. *Materials*, 8(2), 392-407.
81. Zhu, B., Huang, C., Feng, Y., Zhao, J., and Jiang, T. (2010). Dual band switchable metamaterial electromagnetic absorber. *Progress In Electromagnetics Research*, 24, 121-129.
82. Sihvola, A. (2007). Metamaterials in electromagnetics. *Metamaterials*, 1(1), 2-11.
83. Bağmancı, M., Karaaslan, M., Unal, E., and Karadağ, F. Microstrip Patch Antennas Covered with Chiral Metamaterial Structures.
84. Zhi-ning, C. H. E. N. (2014). Metamaterials and metamaterial-based antenna technology. *上海大学学报 (自然科学版)*, (2014 年 05), 531-540.
85. Ali, T., and Biradar, R. C. (2017). A compact multiband antenna using $\lambda/4$ rectangular stub loaded with metamaterial for IEEE 802.11/n and IEEE 802.16 E. *Microwave and Optical Technology Letters*, 59(5), 1000-1006.
86. Kulkarni, N., and Lohiya, G. (2016). A Compact Microstrip Patch Antenna using Metamaterial. *International Journal of Engineering Trends and Technology*, 42(7), 365-369.
87. Ripin, N., Saidy, W. M. A. W., Sulaiman, A. A., Rashid, N. E. A., and Hussin, M. F. (2013, December). Miniaturization of microstrip patch antenna through metamaterial approach. In 2013 IEEE Student Conference on Research and Development (pp. 365-369). IEEE.
88. Lou, R. K. M., Aribi, T., and Ghobadi, C. (2010, December). Improvement of characteristics of microstrip antenna using of metamaterial superstrate. In Proc. International Conf. on Communications Engineering (pp. 22-24).
89. Huang, H., Liu, Y., Zhang, S., and Gong, S. (2014). Multiband metamaterial-loaded monopole antenna for WLAN/WiMAX applications. *IEEE antennas and wireless propagation letters*, 14, 662-665.

90. Gangwar, D., Das, S., and Yadava, R. L. (2013, December). Multiband microstrip stacked patch antenna using CSRR. In 2013 International Conference on Microwave and Photonics (ICMAP) (pp. 1-4). IEEE.
91. Chen, Z. N., Qing, X., Shi, J., and Liu, W. (2015, December). Metamaterial-based antennas: Engineering designs. In 2015 Asia-Pacific Microwave Conference (APMC) (Vol. 1, pp. 1-3). IEEE.
92. Kumar, V., and Wu, Y. (2018). Metamaterial Based Circular Disc Patch Antenna Miniaturization. *Advanced Electromagnetics*, 7(5), 137-144.
93. Kumar, A. S., Cheriyan, R., Ansal, K. A., and Jose, D. S. Metamaterial Inspired CPW Fed Multiband Antenna for IoT Applications.
94. Aggarwal, I., Tripathy, M. R., and Pandey, S. (2016, November). Metamaterial inspired multiband slotted antenna for application in IoT band. In 2016 Online International Conference on Green Engineering and Technologies (IC-GET) (pp. 1-4). IEEE.
95. Feng, S. and Halterman, K. (2008). Parametrically shielding electromagnetic fields by nonlinear metamaterials. *Physical Review Letters*, 100(6). <https://doi.org/10.1103/physrevlett.100.063901>.
96. Rao, S. M., Wilton, D. R., and Glisson, A. W. (1982). Electromagnetic scattering by surfaces of arbitrary shape. *IEEE Transactions on Antennas and Propagation*, 30(3), 409-418. <https://doi.org/10.1109/tap.1982.1142818>.
97. Baccarelli, P., Calcaterra, A., Frezza, F., Frezza, F., Ricciardella, N., Simeoni, P., and Tedeschi, N. (2021). Verification of the electromagnetic deep-penetration effect in the real world. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-021-95080-w>.
98. Marongiu, E., Fanti, A., Pavone, S. C., Lodi, M., Melis, A., Curreli, N., and Mazzarella, G. (2022). Design and characterization of modified comb patch antennas. *IEEE Access*, 10, 36220-36232. <https://doi.org/10.1109/access.2022.3164072>.
99. Guo, H. and Ofori, A. A. (2020). Joint channel and antenna modelling for magnetic induction communication in inhomogeneous media. *IEEE Open Journal of the Communications Society*, 1, 1457-1469. <https://doi.org/10.1109/ojcoms.2020.3026952>
100. Hosseininejad, S. M. and Komjani, N. (2016). Waveguide-fed tunable terahertz antenna based on hybrid graphene-metal structure. *IEEE Transactions on Antennas and Propagation*, 64(9), 3787-3793. <https://doi.org/10.1109/tap.2016.2583538>
101. Du, B., Cai, M., Wang, X., Qian, J., He, C., and Shui, A. (2021). Enhanced electromagnetic wave absorption property of binary zno/nico₂o₄ composites. *Journal of Advanced Ceramics*, 10(4), 832-842. <https://doi.org/10.1007/s40145-021-0476-z>.
102. Ruppin, R. (2000). Extinction properties of a sphere with negative permittivity and permeability. *Solid State Communications*, 116(8), 411-415. [https://doi.org/10.1016/s0038-1098\(00\)00362-8](https://doi.org/10.1016/s0038-1098(00)00362-8).
103. Harrington, R. F. (2001). Time-harmonic electromagnetic fields.

104. Hamad, A. H. and Mian, A. (2018). Radio frequency response of flexible microstrip patch antennas under compressive and bending loads using multiphysics modelling approach. *International Journal of RF and Microwave Computer-Aided Engineering*, 29(3), e21649. <https://doi.org/10.1002/mmce.21649>.
105. Boudkhil, A., Chetloul, M., Benabdellah, N., and Benahmed, N. (2018). Development and performance enhancement of mems helix antenna for THz applications using 3d HFSS-based efficient electromagnetic optimization. *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, 16(1), 210.
106. Melo, M. G. d., Santos, P. A., Faustino, E., Bastos-Filho, C. J. A., and Cerqueira, S. A. (2022). Computational intelligence-based methodology for antenna development. *IEEE Access*, 10, 1860-1870. <https://doi.org/10.1109/access.2021.3137198>.
107. Zainud-Deen, S. H., Shaker, A., and Mahmoud, K. R. (2013). B13. design of notched ultra-wideband antenna with irregular radiator shape using bacterial swarm optimization (BSO) algorithm. 2013 30th National Radio Science Conference (NRSC). <https://doi.org/10.1109/nrsc.2013.6587908>.
108. Mauro, G. S., Torrisi, G., Pidatella, A., Galatà, A., and Mascali, D. (2022). Numerical design of RF antennas for ion cyclotron resonance heating in ecris environment. *Journal of Physics: Conference Series*, 2244(1), 012023. <https://doi.org/10.1088/1742-6596/2244/1/012023>.
109. Agastra, E., Pelosi, G., and Selleri, S. (2013). Attachment modes in the method of moments in time-domain. *Progress in Electromagnetics Research B*, 46, 317-336. <https://doi.org/10.2528/pierb12101702>.
110. Liu, Z., Xi, L., Bao, Y., and Cheng, Z. (2022). Pmchwt solver accelerated by adaptive cross approximation for efficient computation of scattering from metal nanoparticles. *Micromachines*, 13(7), 1086. <https://doi.org/10.3390/mi13071086>.
111. Paula, I. L. d., Lemey, S., Bosman, D., Brande, Q. V. d., Caytan, O., Lambrecht, J., and Rogier, H. (2021). Cost-effective high-performance air-filled SIW antenna array for the global 5G 26 GHz and 28 GHz bands. *IEEE Antennas and Wireless Propagation Letters*, 20(2), 194-198. <https://doi.org/10.1109/lawp.2020.3044114>.
112. Khodaei, F. G., Nourinia, J., and Ghobadi, a. C. (2008). A practical miniaturized u-slot patch antenna with enhanced bandwidth. *Progress in Electromagnetics Research B*, 3, 47-62. <https://doi.org/10.2528/pierb07112201>.
113. Wang, D. and Chan, C. H. (2016). Multiband antenna for WIFI and WIGIg communications. *IEEE Antennas and Wireless Propagation Letters*, 15, 309-312. <https://doi.org/10.1109/lawp.2015.2443013>.
114. Wang, D., Siame, B., Zhang, S., Wang, G., Ju, X., Li, J., and Reaney, I. M. (2020). Direct integration of cold sintered, temperature-stable bi2mo2o9-k2moo4 ceramics on printed circuit boards for satellite navigation antennas. *Journal of the European Ceramic Society*, 40(12), 4029-4034. <https://doi.org/10.1016/j.jeurceramsoc.2020.04.025>.

115. Lundquist, J. D., Linkous, L., Hasni, U., and Topsakal, E. (2023). Indirect applications of additive manufacturing for antennas. *IEEE Open Journal of Antennas and Propagation*, 4, 434-445. <https://doi.org/10.1109/ojap.2023.3265691>.
116. Helena, D., Ramos, A., Varum, T., and Matos, J. N. (2020). Antenna design using modern additive manufacturing technology: a review. *IEEE Access*, 8, 177064-177083. <https://doi.org/10.1109/access.2020.3027383>.
117. Lin, T. Y., Do, T., Kwon, P., and Lillehoj, P. B. (2017). 3d printed metal molds for hot embossing plastic microfluidic devices. *Lab on a Chip*, 17(2), 241-247. <https://doi.org/10.1039/c6lc01430e>.
118. Alkaraki, S., Andy, A. S., Gao, Y., Tong, K., Ying, Z., Donnan, R. S., and Parini, C. (2018). Compact and low-cost 3-d printed antennas metalized using spray-coating technology for 5G mm-wave communication systems. *IEEE Antennas and Wireless Propagation Letters*, 17(11), 2051-2055. <https://doi.org/10.1109/lawp.2018.2848912>.
119. Ferrando-Rocher, M., Herranz-Herruzo, J. I., Valero-Nogueira, A., and Bernardo-Clemente, B. (2018). Performance assessment of gap-waveguide array antennas: cnc milling versus three-dimensional printing. *IEEE Antennas and Wireless Propagation Letters*, 17(11), 2056-2060. <https://doi.org/10.1109/lawp.2018.2833740>.
120. Chou, J. and Su, S. (2008). Very-low-cost copper-wire antenna for 2.4-GHz WLAN operation. *Microwave and Optical Technology Letters*, 50(8), 2107-2109. <https://doi.org/10.1002/mop.23589>.
121. Shingne, V., Jeyakumar, A., and S, B. N. (2015). Effect of wire monopole antenna for different feed position. *International Journal of Innovative Research in Computer and Communication Engineering*, 03(06), 5007-5011.
122. Potyrailo, R. A., Nagraj, N., Tang, Z., Mondello, F. J., Surman, C. M., and Morris, W. (2012). Battery-free radio frequency identification (RFID) sensors for food quality and safety. *Journal of Agricultural and Food Chemistry*, 60(35), 8535-8543. <https://doi.org/10.1021/jf302416y>.
123. Kejřík, L., Horák, M., Šikola, T., and Křápek, V. (2020). Structural and optical properties of monocrystalline and polycrystalline gold plasmonic nanorods. <https://doi.org/10.48550/arxiv.2008.11676/>
124. Perumalsamy, M. (2021). Multiband microstrip patch antenna using copper nano radiating element for X band and C band applications. *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, 34(6). <https://doi.org/10.1002/jnm.2897/>
125. Ghassemiparvin, B. and Ghalichechian, N. (2019). Design, fabrication, and testing of a helical antenna using 3D printing technology. *Microwave and Optical Technology Letters*, 62(4), 1577-1580. <https://doi.org/10.1002/mop.32184>.
126. Sakurai, J., Hata, S., and Shimokohbe, A. (2005). Novel fabrication method of metallic glass thin films using carousel-type sputtering system. *SPIE Proceedings*. <https://doi.org/10.1117/12.581811>.

127. Mohammed, B. A. D. A. and Sali, A. (2020). Electro-textile wearable antennas in wireless body area networks: materials, antenna design, manufacturing techniques, and human body consideration—a review. *Textile Research Journal*, 91(5-6), 646-663. <https://doi.org/10.1177/0040517520932230>.
128. Goliya, Y., Rivadeneyra, A., Salmeron, J. L., Albrecht, A., Mock, J., Haider, M., and Bobinger, M. (2019). Next generation antennas based on screen-printed and transparent silver nanowire films. *Advanced Optical Materials*, 7(21), 1900995. <https://doi.org/10.1002/adom.201900995>.
129. Bagheri, S., Weber, K., Gissibl, T., Weiss, T. G., Neubrech, F., and Giessen, H. (2015). Fabrication of square-centimeter plasmonic nanoantenna arrays by femtosecond direct laser writing lithography: effects of collective excitations on seira enhancement. *ACS Photonics*, 2(6), 779-786. <https://doi.org/10.1021/acsphotonics.5b00141>.
130. Rabbani, M. S. and Ghafouri-Shiraz, H. (2016). Improvement of microstrip patch antenna gain and bandwidth at 60 GHz and X bands for wireless applications. *IET Microwaves, Antennas & Propagation*, 10(11), 1167-1173.
131. Wang, X., Liu, X., Zhang, W., Hao, D., and Liu, a. Y. (2021). Surface-mount pifa using ball grid array packaging for 5G mm-wave. *Progress in Electromagnetics Research Letters*, 98, 55-60. <https://doi.org/10.2528/pierl21050203>.
132. Liu, X., Zhang, W., Hao, D., and Liu, a. Y. (2021). A compact broadband folded dipole antenna element with ball grid array packaging for new 5G application. *Progress in Electromagnetics Research Letters*, 96, 113-119. <https://doi.org/10.2528/pierl21010502>.
133. Anagnostou, D. E., Zheng, G., Chryssomallis, M. T., Lyke, J. C., Ponchak, G. E., Papapolymerou, J., and Christodoulou, C. G. (2006). Design, fabrication, and measurements of an RF-MEMS-based self-similar reconfigurable antenna. *IEEE Transactions on Antennas and Propagation*, 54(2), 422-432.
134. Pranonsatit, S., Holmes, A. S., and Lucyszyn, S. (2010, December). Sectorised horn antenna array using an RF MEMS rotary switch. In 2010 Asia-Pacific Microwave Conference (pp. 1909-1913). IEEE.
135. Wright, M. D., Baron, W., Miller, J., Tuss, J., Zeppettella, D., and Ali, M. (2018). MEMS reconfigurable broadband patch antenna for conformal applications. *IEEE Transactions on Antennas and Propagation*, 66(6), 2770-2778.
136. Zhao, X., Riaz, S., Geng, S. (2019). A Reconfigurable MIMO/UWB MIMO Antenna for Cognitive Radio Applications. *IEEE Access*, (7), 46739-46747.
137. Parchin, N. O., Basherlou, H. J., Al-Yasir, Y. I. A., Abdulkhaleq, A. M., Abd-Alhameed, R. A. (2020). Reconfigurable Antennas: Switching Techniques—a Survey. *Electronics*, 2(9), 336. <https://doi.org/10.3390/electronics9020336>.
138. Majid, H. A., Rahim, M. K. A., Hamid, M. R., Ismail, M. H. (2014). Frequency Reconfigurable Microstrip Patch-slot Antenna with Directional Radiation Pattern. *Progress in Electromagnetics Research*, (144), 319-328. <https://doi.org/10.2528/pier13102901>.

139. Saraswat, K. and Harish, A. R. (2019). Flexible Dual-band Dual-polarised CPW-fed Monopole Antenna with Discrete-frequency Reconfigurability. *IET Microwaves, Antennas & Propagation*, 12(13), 2053-2060. <https://doi.org/10.1049/iet-map.2018.5711>.
140. Costantine, J., Tawk, Y., Barbin, S. E., and Christodoulou, C. G. (2015). Reconfigurable antennas: Design and applications. *Proceedings of the IEEE*, 103(3), 424-437.
141. Christodoulou, C. G., Tawk, Y., Lane, S. A., and Erwin, S. R. (2012). Reconfigurable antennas for wireless and space applications. *Proceedings of the IEEE*, 100(7), 2250-2261.
142. Bernhard, J. T. (2003). Reconfigurable antennas and apertures: state of the art and future outlook. *Smart Structures and Materials 2003: Smart Electronics, MEMS, BioMEMS, and Nanotechnology*, 5055, 1-9.
143. Bernhard, J. T. (2007, August). Reconfigurable multifunction antennas: Next steps for the future. In 2007 International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications (pp. K2-1). IEEE.
144. Ali, M. (2021). Reconfigurable antenna design and analysis. Artech House.
145. Koul, S. K., and Singh, R. K. (2022). Reconfigurable Active and Passive Planar Antennas for Wireless Communication Systems. Springer Nature.
146. Kumar, N., Kumar, P., and Sharma, M. (2020). Reconfigurable antenna and performance optimization approach. *Wireless Personal Communications*, 112, 2187-2212.
147. Huang, Y. (2021). Antennas: from theory to practice. John Wiley & Sons.
148. Antennas: From Theory to Practice, 2nd Edition. (2021, September 14). Retrieved from <https://www.wiley.com/en-us/Antennas%3A+From+Theory+to+Practice%2C+2nd+Edition-p-9781119092322>.
149. Kanaujia, B. K., Gupta, S. K., Kishor, J., and Gangwar, D. (Eds.). (2020). Printed Antennas: Theory and Design. CRC Press.
150. Dubal, S., and Chaudhari, A. (2020, January). Mechanisms of reconfigurable antenna: A review. In 2020 10th International Conference on Cloud Computing, Data Science & Engineering (Confluence) (pp. 576-580). IEEE.
151. Pandey, A. (2019). Practical microstrip and printed antenna design. Artech House.
152. Ramahatla, K., Mosalaosi, M., Yahya, A., and Basutli, B. (2022). Multiband reconfigurable antennas for 5G wireless and CubeSat applications: A review. *IEEE Access*, 10, 40910-40931.
153. Kamran Shereen, M., Khattak, M. I., and Witjaksono, G. (2019). A brief review of frequency, radiation pattern, polarization, and compound reconfigurable antennas for 5G applications. *Journal of Computational Electronics*, 18(3), 1065-1102.

154. Yuan, X., Li, Z., Rodrigo, D., Mopidevi, H., Kaynar, O., Jofre, L., and Cetiner, B. A. (2012). A parasitic layer-based reconfigurable antenna design by multi-objective optimization. *IEEE Transactions on Antennas and Propagation*, 60(6), 2690-2701. <https://doi.org/10.1109/tap.2012.2194663>.
155. Towfiq, M. A., Khalat, A., Blanch, S., Romeu, J., Jofre, L., and Çetiner, B. A. (2019). Error vector magnitude, intermodulation, and radiation characteristics of a bandwidth- and pattern-reconfigurable antenna. *IEEE Antennas and Wireless Propagation Letters*, 18(10), 1956-1960. <https://doi.org/10.1109/lawp.2019.2933379>.
156. Chen, Z. N., Liu, D., Nakano, H., Qing, X., and Zwick, T. (2016). Handbook of antenna technologies. Springer Publishing Company, Incorporated.
157. Mohanta, H. C., Kouzani, A., and Mandal, S. K. (2019). Reconfigurable antennas and their applications.
158. Yang, F. and Rahmat-Samii, Y. (2008). Electromagnetic band gap structures in antenna engineering. <https://doi.org/10.1017/cbo9780511754531>.
159. Hussain, R., Aljaloud, K., Rao, A. R., Aziz, A., Aladadi, Y. T., Alqahtani, A. H., and Alhuwimel, S. (2022). Slot-based Cube-sat antenna with wide tuning capabilities. *Microwave and Optical Technology Letters*, 65(6), 1664-1669. <https://doi.org/10.1002/mop.33593>.
160. Mariem, M. and Ali, G. (2021). Designs of frequency reconfigurable planar bow-tie antenna integrated with pin, varactor diodes and parasitic elements. *Advances in Science, Technology and Engineering Systems Journal*, 6(4), 320-326. <https://doi.org/10.25046/aj060435>.
161. AI-Yasir, Y. I., OjaroudiParchin, N., Alabdullah, A., Mshwat, W., Ullah, A., and Abd-Alhameed, R. A. (2019). New pattern reconfigurable circular disk antenna using two pin diodes for WIMAX/WI-FI (IEEE 802.11/a) applications. 2019 16th International Conference on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design.
162. Mansoul, A., Ghanem, F., Hamid, M. R., Salonen, E., and Berg, M. (2016). Bandwidth reconfigurable antenna with a fixed lower and a variable upper limit. *IET Microwaves, Antennas & Propagation*, 10(15), 1725-1733. <https://doi.org/10.1049/iet-map.2016.0286>.
163. Sharma, S. C., Fideles, F., and Kalikond, A. (2013). Planar yagi-uda antenna with reconfigurable radiation patterns. *Microwave and Optical Technology Letters*, 55(12), 2946-2952. <https://doi.org/10.1002/mop.27950>.
164. Li, K., Cai, Y., Yin, Y., and Hu, W. (2018). A wideband e-plane pattern reconfigurable antenna with enhanced gain. *International Journal of RF and Microwave Computer-Aided Engineering*, 29(2), e21530. <https://doi.org/10.1002/mmce.21530>.
165. Mohamadzade, B., Hashmi, R. M., Maric, S., Lalbakhsh, A., Esselle, K. P., and Hashmi, R. M. (2020). Recent developments and state of the art in flexible and conformal reconfigurable antennas. *Electronics*, 9(9), 1375. <https://doi.org/10.3390/electronics9091375>.

166. Li, W., Gao, S., Cai, Y., Luo, Q., Sobhy, M., Wei, G., and Cheng, Z. (2017). Polarization-reconfigurable Circularly Polarized Planar Antenna Using Switchable Polarizer. *IEEE Transactions on Antennas and Propagation*, 9(65), 4470-4477. <https://doi.org/10.1109/tap.2017.2730240>.
167. Zhang, H., Chen, X., Wang, Z., Ge, Y., Pu, J. (2019). A 1-bit Electronically Reconfigurable Reflectarray Antenna in X Band. *IEEE Access*, (7), 66567-66575. <https://doi.org/10.1109/access.2019.2918231>.
168. Motovilova, E. and O'Sullivan, B. (2020). A Review on Reconfigurable Liquid Dielectric Antennas. *Materials*, 8(13), 1863. <https://doi.org/10.3390/ma13081863>.
169. Baliga, B. (2008). Fundamentals of power semiconductor devices. <https://doi.org/10.1007/978-0-387-47314-7>.
170. Shirazi, M., Li, T., and Gong, X. (2015). Effects of pin diode switches on the performance of reconfigurable slot-ring antenna. 2015 IEEE 16th Annual Wireless and Microwave Technology Conference (WAMICON). <https://doi.org/10.1109/wamicon.2015.7120388>.
171. Sharma, S. and Tripathi, C. C. (2015). Frequency reconfigurable u-slot antenna for SDR application. *Progress in Electromagnetics Research Letters*, 55, 129-136. <https://doi.org/10.2528/pierl15071304>.
172. Luo Y, Liu H, He Y, Cui H, Yang G. Continuous Resonance Tuning without Blindness by Applying Nonlinear Properties of PIN Diodes. *Sensors*. 2021; 21(8):2816. <https://doi.org/10.3390/s21082816>.
173. Carr, J. (2002). RF components and circuits. Newnes.
174. Gilmore, R., and Besser, L. (2003). Practical RF Circuit Design for Modern Wireless Systems: Active Circuits and Systems, Volume 2 (Vol. 2). Artech House.
175. Sahu, N. K., and Sharma, A. K. (2017, May). An investigation of pattern and frequency reconfigurable microstrip slot antenna using PIN diodes. In 2017 Progress In Electromagnetics Research Symposium-Spring (PIERS) (pp. 971-976). IEEE.
176. Elluru, D., Awasthi, A. K., Gogineni, P., Taylor, R., Shahabi, A., Lemmon, A. N., and Lee, J. I. (2022). Design of an absorptive high-power pin diode switch for an ultra-wideband radar. *IEEE Journal of Microwaves*, 2(2), 286-296. <https://doi.org/10.1109/jmw.2021.3138889>.
177. Almawgani, A. H. M., Devi, Y. U., Madhav, B. T. P., and Alhawari, A. R. H. (2023). Design and analysis of frequency reconfigurable antenna for wideband millimeter-wave communications. <https://doi.org/10.21203/rs.3.rs-2709762/v1>.
178. Cuong, H. Q., Le, M. D., Dinh, N. Q., Tran, X. N., and Michishita, N. (2023). A broadband 1-bit single-layer reconfigurable reflectarray unit cell based on pin diode model. *IEEE Access*, 11, 6477-6489. <https://doi.org/10.1109/access.2023.3237764>.
179. Baliga, B. J. (2019). Fundamentals of power semiconductor devices. <https://doi.org/10.1007/978-3-319-93988-9>.

180. Orugu, R., Nesasudha, M., and Janapala, D. K. (2021, January). A Frequency Tunable Hexagon Shaped Antenna for 5.8 GHz-WiFi and Sub 6-5G Mobile IoT Applications. In 2021 International Conference on Computer Communication and Informatics (ICCCI) (pp. 1-4). IEEE.
181. Majid, H. A., Rahim, M. K. A., Hamid, M. R., and Ismail, M. F. (2012). A compact frequency-reconfigurable narrowband microstrip slot antenna. *IEEE antennas and wireless propagation letters*, 11, 616-619.
182. Paik, H., and Paik, S. (2021, August). A frequency reconfigurable printed antenna using PIN diode for mobile terminal application. In 2021 Asian Conference on Innovation in Technology (ASIANCON) (pp. 1-4). IEEE.
183. Bokran-Charkh, M., Nasser-Moghadasi, M., Sadeghzadeh, R. A., and Pedram, K. (2017, December). Microstrip compact antenna with reconfigurable characteristic and circular polarization for WLAN application. In 2017 IEEE 4th International Conference on Knowledge-Based Engineering and Innovation (KBEI) (pp. 0330-0334). IEEE.
184. Chang, M., Han, J., Li, Y., Ma, X., Liu, H., and Li, L. (2023). Self-Powered Polarization-Reconfigurable Rectenna for Wireless Power Transfer System. *IEEE Transactions on Antennas and Propagation*.
185. Infineon Technologies BBY58-02W E6327. (n.d.). Retrieved from <https://www.digikey.hk/en/products/detail/rochester-electronics-llc/BBY58-02W-E6327/12096451>
186. Broadcom Limited HSMP-3814-TR1G. (n.d.). Retrieved from <https://www.digikey.com/en/products/detail/broadcom-limited/HSMP-3814-TR1G/1118759>
187. Tawk, Y., Bkassiny, M., El-Howayek, G., Jayaweera, S. K., Avery, K. N. L., and Christodoulou, C. G. (2011). Reconfigurable front-end antennas for cognitive radio applications. *IET Microwaves, Antennas & Propagation*, 5(8), 985. <https://doi.org/10.1049/iet-map.2010.0358>.
188. Nasir, A. A., Zhou, X., Durrani, S., and Kennedy, R. A. (2015). Wireless-powered relays in cooperative communications: time-switching relaying protocols and throughput analysis. *IEEE Transactions on Communications*, 63(5), 1607-1622. <https://doi.org/10.1109/tcomm.2015.2415480>.
189. Ra'di, Y., Nikmehr, S., and Poorziad, A. (2011). A novel bandwidth enhancement technique for x-band rf mems actuated reconfigurable reflectarray. *Progress in Electromagnetics Research*, 111, 179-196. <https://doi.org/10.2528/pier10101201>.
190. Kingsley, N., Anagnostou, D. E., Tentzeris, M. M., and Papapolymerou, J. (2007). Rf mems sequentially reconfigurable sierpinski antenna on a flexible organic substrate with novel dc-biasing technique. *Journal of Microelectromechanical Systems*, 16(5), 1185-1192. <https://doi.org/10.1109/jmems.2007.902462>.
191. Tsai, Z., Jiang, Y., Lee, J. S. H., Lin, K., and Wang, H. (2007). Analysis and design of bandpass single-pole-double-throw fet filter-integrated switches. *IEEE Transactions on*

- Microwave Theory and Techniques*, 55(8), 1601-1610. <https://doi.org/10.1109/tmtt.2007.901132>.
192. Shairi, N. A., Ahmad, B. H., and Wong, a. P. W. (2013). Bandstop to allpass reconfigurable filter technique in spdt switch design. *Progress in Electromagnetics Research C*, 39, 265-277. <https://doi.org/10.2528/pierc13040313>.
 193. Zolkefli, A. A., Ahmad, B. H., Shairi, N. A., Othman, A., Zakaria, Z., Ibrahim, I. M., and Majid, H. A. (2021). SPDT discrete switch design using switchable SIW resonators for millimeter wave MIMO transceiver. *Indonesian Journal of Electrical Engineering and Computer Science*, 24(3), 1542. <https://doi.org/10.11591/ijeecs.v24.i3.pp1542-1549>.
 194. Zhang, F., Li, C., Di, M., Pan, Z., Li, C., Cahoon, N., and Wang, A. (2020). Design and analysis of a 28ghz 9kv esd-protected distributed travelling wave TR-X switch in 22nm fdsoi. *IEEE Journal of the Electron Devices Society*, 8, 655-661. <https://doi.org/10.1109/jeds.2020.2975598>.
 195. Dildar, H., Althobiani, F., Ahmad, I., Khan, W., Ullah, S., Mufti, N., and Irfan, M. (2020). Design and experimental analysis of multiband frequency reconfigurable antenna for 5G and sub-6 GHz wireless communication. *Micromachines*, 12(1), 32. <https://doi.org/10.3390/mi12010032>.
 196. Trzebiatowski, K., Rzymowski, M., Kulas, L., and Nyka, K. (2021). Simple 60 GHz switched beam antenna for 5g millimeter-wave applications. *IEEE Antennas and Wireless Propagation Letters*, 20(1), 38-42. <https://doi.org/10.1109/lawp.2020.3038260>.
 197. Shairi, N. A., Sanusi, N. M., Othman, A., Zakaria, Z., and Ibrahim, I. M. (2019). Performance analysis of ultra-wideband rf switch using discrete pin diode in sc-79 package for medical application of microwave imaging. *International Journal of Electrical and Computer Engineering (IJECE)*, 9(6), 4668. <https://doi.org/10.11591/ijece.v9i6.pp4668-4674>.
 198. Shahmirzadi, N. V. and Oraizi, H. (2016). Design of reconfigurable coplanar waveguide-fed planar antenna for multiband multi-input–multi-output applications. *IET Microwaves, Antennas & Propagation*, 10(14), 1591-1597. <https://doi.org/10.1049/iet-map.2016.0316>.
 199. Sato, H., Quan, P. Q., Eguchi, K., Koyanagi, Y., Morishita, H., and Takahashi, M. (2023). A study on reduction of electromagnetic coupling between symmetric antennas using even-odd mode analysis. *IEICE Communications Express*, 12(5), 205-210. <https://doi.org/10.1587/comex.2023xbl0001>.
 200. Behdad, N. and Sarabandi, K. (2006). Dual-band reconfigurable antenna with a very wide tunability range. *IEEE Transactions on Antennas and Propagation*, 54(2), 409-416. <https://doi.org/10.1109/tap.2005.863412>.
 201. Li, T., Zhai, H., Wang, X., Li, L., and Liang, C. (2015). Frequency-reconfigurable bow-tie antenna for bluetooth, wimax, and wlan applications. *IEEE Antennas and Wireless Propagation Letters*, 14, 171-174. <https://doi.org/10.1109/lawp.2014.2359199>.

202. Qiu, P., Feng, Q., Miyahara, K., and Kanaya, H. (2022). Multi-bands antenna for metal-rimmed handset terminals. *Microwave and Optical Technology Letters*, 64(4), 738-743. <https://doi.org/10.1002/mop.33149>.
203. Ren, A., Huang, Z., Yang, L., Liu, Y., and Yu, H. (2021). Ground radiation antenna utilizing characteristic mode theory. *International Journal of RF and Microwave Computer-Aided Engineering*, 31(10). <https://doi.org/10.1002/mmce.22804>.
204. Althuwayb, A. A., Alibakhshikenari, M., Virdee, B. S., Falcone, F., and Limiti, E. (2021). Overcoming inherent narrow bandwidth and low radiation properties of electrically small antennas by using an active interior-matching circuit. *IEEE Access*, 9, 20622-20628. <https://doi.org/10.1109/access.2021.3054939>.
205. Seo, Y. and Lim, S. (2016). Dipole- and loop-mode switchable origami paper antenna. *Microwave and Optical Technology Letters*, 58(3), 668-672. <https://doi.org/10.1002/mop.29647>.
206. Ali, A., Wang, H., Lee, J., Ahn, Y. H., and Park, I. (2021). Ultra-low profile solar-cell-integrated antenna with a high form factor. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-021-00461-w>.
207. Hoang, T., Le, T. T., and Park, H. (2016). Bandwidth improvement of a circularly polarised printed monopole antenna using a lumped capacitor. *Electronics Letters*, 52(13), 1091-1092. <https://doi.org/10.1049/el.2016.1277>.
208. Liao, Y., Hubing, T. H., and Su, D. (2012). Equivalent circuit for dipole antennas in a lossy medium. *IEEE Transactions on Antennas and Propagation*, 60(8), 3950-3953. <https://doi.org/10.1109/tap.2012.2201112>.
209. Al-Omari, M., Attia, H., Qureshi, K. K., and Sheikh, S. I. (2023). Design of frequency-reconfigurable antenna on dielectric and magnetic metamaterial composite substrate. *IEEE Antennas and Wireless Propagation Letters*, 22(4), 943-947. <https://doi.org/10.1109/lawp.2022.3230827>.
210. Cao, Y., Cheung, S. W., Sun, X., and Yuk, T. I. (2013). Frequency-reconfigurable monopole antenna with wide tuning range for cognitive radio. *Microwave and Optical Technology Letters*, 56(1), 145-152. <https://doi.org/10.1002/mop.28070>.
211. Ilvonen, J., Valkonen, R., Holopainen, J., and Viikari, V. (2014). Multiband frequency reconfigurable 4G handset antenna with MIMO capability. *Progress in Electromagnetics Research*, 148, 233-243. <https://doi.org/10.2528/pier14062703>.
212. Mirzaei, H. and Eleftheriades, G. V. (2011). A compact frequency-reconfigurable metamaterial-inspired antenna. *IEEE Antennas and Wireless Propagation Letters*, 10, 1154-1157. <https://doi.org/10.1109/lawp.2011.2172180>.
213. Alibakhshikenari, M., Virdee, B. S., Shukla, P., Parchin, N. O., Azpilicueta, L., See, C. H., and Limiti, E. (2020). Metamaterial-inspired antenna array for application in microwave breast imaging systems for tumor detection. *IEEE Access*, 8, 174667-174678. <https://doi.org/10.1109/access.2020.3025672>.

214. 2019: Coll-Perales, B., Gozálvez, J., and Gruteser, M. (2019). Sub-6ghz assisted mac for millimeter wave vehicular communications. *IEEE Communications Magazine*, 57(3), 125-131. <https://doi.org/10.1109/mcom.2019.1800509>.
215. Sarkar, D., Saurav, K., and Srivastava, K. D. (2014). Multi-band microstrip-fed slot antenna loaded with split-ring resonator. *Electronics Letters*, 50(21), 1498-1500. <https://doi.org/10.1049/el.2014.2625>.
216. Sreelekshmi, S.; Sankar, S.P. A square ring and single split resonator based wearable antenna for Microwave energy harvesting for IoT nodes. *Sustain. Energy Technol. Assess.* 2022, 52, 102217.
217. Li, Y.; Feng, Q. A compact tri-band monopole antenna with metamaterial loaded for WLAN/WiMAX applications. *J. Electromagn. Waves Appl.* 2013, 27, 772–782.
218. Chen, X.; Chen, J.; Liu, C.; Huang, K. A genetic metamaterial and its application to gain improvement of a patch antenna. *J. Electromagn. Waves Appl.* 2012, 26, 1977–1985.
219. Kumar, N.; Gupta, S.C. Analyzing the performance of a microstrip patch antenna with metamaterial cover by varying the distance and dielectric constant in between. *J. Electromagn. Waves Appl.* 2015, 29, 2428–2443.
220. Hussain, A.; Dong, J.; Abdulkarim, Y.I.; Wu, R.; Muhammadsharif, F.F.; Shi, R.; Howlader, M.M.R. A double negative (DNG) metamaterial based on parallel double-E square split resonators for multi-band applications: Simulation and experiment. *Results Phys.* 2023, 46, 106302.
221. Ullah, S.; Ahmad, S.; Khan, B.A.; Tahir, F.A.; Flint, J.A. An hp-shape hexa-band antenna for multi-standard wireless communication systems. *Wirel. Netw.* 2019, 25, 1361–1369.
222. Balanis, C.A. *Antenna Theory: Analysis and Design*; John Wiley & Sons: Hoboken, NJ, USA, 2016.
223. Ghaffar, A.; Li, X.J.; Awan, W.A.; Iffat Naqvi, S.; Hussain, N.; Seet, B.C.; Limiti, E. Design and realization of a frequency reconfigurable multimode antenna for ISM, 5G-sub-6-GHz, and S-band applications. *Applied Sciences*. 2021, 11, 1635.
224. Bahl, I.J. A designer's guide to microstrip line. *Microwaves* 1977, 16, 174–182.
225. California Eastern Laboratories. L, S-Band High Power SPDT RF Switch CG2415M6 Datasheet. Available online: <https://www.cel.com/documents/datasheets/CG2415M6.pdf> (accessed on 1 September 2017).
226. Zhao, X.; Riaz, S. A dual-band frequency reconfigurable MIMO patch-slot antenna based on reconfigurable microstrip feedline. *IEEE Access* 2018, 6, 41450–41457.
227. Han, L.; Wang, C.; Chen, X.; Zhang, W. Compact frequency-reconfigurable slot antenna for wireless applications. *IEEE Antennas Wirel. Propag. Lett.* 2016, 15, 1795–1798.

228. Arun, V.; Marx, L.K. Internet of Things controlled reconfigurable antenna for RF harvesting. *Def. Sci. J.* 2018, 68, 566–571.
229. Zaidi, A.; Awan, W.A.; Hussain, N.; Baghdad, A. A Wide and Tri-band Flexible Antennas with Independently Controllable Notch Bands for Sub-6-GHz Communication System. *Radioengineering* 2020, 29, 44–51.
230. Cai, Y.M.; Li, K.; Yin, Y.; Gao, S.; Hu, W.; Zhao, L. A low-profile frequency reconfigurable grid-slotted patch antenna. *IEEE Access* 2018, 6, 36305–36312.
231. Soltanpour, M.; Fakharian, M.M. Compact filtering slot antenna with frequency agility for Wi-Fi/LTE mobile applications. *Electron. Lett.* 2016, 52, 491–492.
232. Abdulraheem, Y.I.; Oguntala, G.A.; Abdullah, A.S.; Mohammed, H.J.; Ali, R.A.; Abd-Alhameed, R.A.; Noras, J.M. Design of frequency reconfigurable multiband compact antenna using two PIN diodes for WLAN/WiMAX applications. *IET Microw. Antennas Propag.* 2017, 11, 1098–1105.
233. Ali, T.; Khaleeq, M.M.; Biradar, R.C. A multiband reconfigurable slot antenna for wireless applications. *AEU-International J. Electron. Commun.* 2018, 84, 273–280.
234. Ghaffar, A.; Li, X.J.; Awan, W.A.; Iffat Naqvi, S.; Hussain, N.; Seet, B.C.; Limiti, E. Design and realization of a frequency reconfigurable multimode antenna for ISM, 5G-sub-6-GHz, and S-band applications. *Applied Sciences* 2021, 11, 1635.
235. Koç Polat, H.; Geyikoğlu, M.D.; Cavusoğlu, B. Modeling and validation of a new reconfigurable patch antenna through equivalent lumped circuit-based design for minimum tuning effort. *Microw. Opt. Technol. Lett.* 2020, 62, 2335–2345.
236. Shah, I.A.; Hayat, S.; Basir, A.; Zada, M.; Shah, S.A.A.; Ullah, S. Design and analysis of a hexa-band frequency reconfigurable antenna for wireless communication. *AEU-Int. J. Electron. Commun.* 2019, 98, 80–88.
237. Suzdalenko, A.; Chub, A. Current sensorless control for half-bridge-based AC/DC PFC converter with consideration of conduction losses. *Int. J. Circuit Theory Appl.* 2016, 44, 2072–2084.
238. Rabus, D. G. (2007). Integrated ring resonators. Springer-Verlag Berlin Heidelberg.
239. Yariv, A. (2002). Critical coupling and its control in optical waveguide-ring resonator systems. *IEEE Photonics Technology Letters*, 14(4), 483-485.
240. Yariv, A. (2000). Universal relations for coupling of optical power between micro resonators and dielectric waveguides. *Electronics letters*, 36(4), 321-322.
241. Shah, S.A.A.; Khan, M.F.; Ullah, S.; Flint, J.A. Design of a multi-band frequency reconfigurable planar monopole antenna using truncated ground plane for Wi-Fi, WLAN and WiMAX applications. In Proceedings of the 2014 International Conference on Open Source Systems & Technologies, Lahore, Pakistan, 18–20 December 2014; IEEE: Piscataway, NJ, USA, 2014; pp. 151–155.

242. S. Hayat, I. A. Shah, I. Khan, I. Alam, S. Ullah et al., "Design of tetra-band frequency reconfigurable antenna for portable wireless applications," in *Int. Conf. on Intelligent Systems Engineering*, Islamabad, Pakistan, pp. 15–17, 2016.
243. Shah, I.A.; Hayat, S.; Khan, I.; Alam, I.; Ullah, S.; Afridi, A. A compact, tri-band and 9-shape reconfigurable antenna for WiFi, WiMAX and WLAN applications. *Int. J. Wirel. Microw. Technol. (IJWMT)* 2016, 6, 45–53.
244. Saeed, S. M., Balanis, C. A., and Birtcher, C. R. (2016). Inkjet-printed flexible reconfigurable antenna for conformal WLAN/WiMAX wireless devices. *IEEE Antennas and Wireless Propagation Letters*, 15, 1979-1982.
245. Ullah, S.; Hayat, S.; Umar, A.; Ali, U.; Tahir, F.A.; Flint, J.A. Design, fabrication and measurement of triple band frequency reconfigurable antennas for portable wireless communications. *AEU-Int. J. Electron. Commun.* 2017, 81, 236–242.
246. Shah, S.A.A.; Khan, M.F.; Ullah, S.; Basir, A.; Ali, U.; Naeem, U. Design and measurement of planar monopole antennas for multi-band wireless applications. *IETE J. Res.* 2017, 63, 194–204.
247. Iqbal, A.; Ullah, S.; Naeem, U.; Basir, A.; Ali, U. Design, fabrication and measurement of a compact, frequency reconfigurable, modified T-shape planar antenna for portable applications. *J. Electr. Eng. Technol.* 2017, 12, 1611–1618.
248. Ullah, S.; Shaheen, A.; Khan, B.A.; Flint, J.A. A multi-band switchable antenna for Wi-Fi, 3G Advanced, WiMAX, and WLAN wireless applications. *Int. J. Microw. Wirel. Technol.* 2018, 10, 991–997.
249. Saikia, B.; Dutta, P.; Borah, K. Design of a Frequency Reconfigurable Microstrip Patch Antenna for Multiband Applications. In *Proceedings of the 5th International Conference on Computers & Management Skills (ICCM 2019)*, Arunachal Pradesh, India, 15–16 December 2019.
250. Awan, W. A., Hussain, N., Naqvi, S. A., Iqbal, A., Striker, R., Mitra, D., Braaten, B. D. (2020). A miniaturized wideband and multi-band on-demand reconfigurable antenna for compact and portable devices. *AEU-International Journal of Electronics and Communications*, 122, 153266.
251. Dildar, H., Althobiani, F., Ahmad, I., Khan, W. U. R., Ullah, S., Mufti, N., Glowacz, A. (2021). Design and Experimental Analysis of Multiband Frequency Reconfigurable Antenna for 5G and Sub-6 GHz Wireless Communication. *Micromachines*, 12(1), 32.
252. Ahmad, I., Dildar, H., Khan, W. U. R., Ullah, S., Ullah, S., Albreem, M. A., Uthansakul, P. (2021). Frequency Reconfigurable Antenna for Multi Standard Wireless and Mobile Communication Systems. *CMC-COMPUTERS MATERIALS & CONTINUA*, 68(2), 2563-2578.