RECONFIGURABLE BAND NOTCH FILTER FOR COGNITIVE RADIO IN DEFENSE ELECTROVEIL

A PROJECT REPORT

(PHASE – II)

Submitted by

AROKYA JESY A	**REGISTER NO.: 21UEC013**
SHAGIR PARVIN J	**REGISTER NO.: 21UEC167**
SANTHIYA B	**REGISTER NO.: 21UEC158**

Under the guidance of

Dr. N. SARANYA

Assistant Professor

In partial fulfillment of the award of the degree

of

BACHELOR OF TECHNOLOGY

in

ELECTRONICS AND COMMUNICATION ENGINEERING

SRI MANAKULA VINAYAGAR ENGINEERING COLLEGE

(An Autonomous Institution)

MADAGADIPET, PUDUCHERRY-605107

PONDICHERRYUNIVERSITY: PUDUCHERRY-605014

APRIL 2025

SRI MANAKULA VINAYAGAR ENGINEERING COLLEGE

(An Autonomous Institution)

MADAGADIPET, PUDUCHERRY–605 107

BONAFIDE CERTIFICATE

Certified that this project report **"RECONFIGURABLE BAND NOTCH FILTER FOR COGNITIVE RADIO IN DEFENSE ELECTROVEIL"** is the bonafide work of **"AROKYA JESY A [REGISTER NO: 21UEC013], SHAGIR PARVIN J [REGISTER NO: 21UEC167], SANTHIYA B [REGISTER NO: 21UEC158]"** submitted to the Pondicherry University, Puducherry for the award of the degree of **Bachelor of Technology in Electronics and Communication Engineering**. The contents of this project, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Signature	Signature
Dr. P. RAJA	**Dr. N. SARANYA**
Head of the Department	Assistant Professor
	Supervisor

Submitted for the End Semester Examination held on____________________

INTERNAL EXAMINER	**EXTERNAL EXAMINER**

ACKNOWLEDGEMENT

First and foremost, we would like to thank our guide, **Dr.N.Saranya,** Assistant Professor, Department of Electronics and Communication Engineering, for the valuable guidance and advice. She inspired us greatly to work on this project. Her ability to inspire us has made an enormous contribution to our project.

We thank our project coordinator **Dr.N.Saranya**, Assistant Professor, Department of Electronics and Communication Engineering, for her endless support and guidance.

We would like to take this opportunity to express our deepest gratitude to **Dr.P.Raja**, Professor and Head of the Department, Electronics and Communication Engineering, for giving us valuable suggestions. He has always been a source of inspiration and encouragement towards the project.

We would like to take this opportunity to thank our respected Director cum Principal, **Dr.V.S.K.Venkatachalapathy** and our Management for providing us the best ambience to complete this project.

We would like to thank all the Electronics and Communication Engineering Department Teaching Staff and Technical Staff for their support to complete this project.

Finally, for the motivation and assistance in completing this mission, an honorable mention goes to our families and friends. Without their support we would have faced many challenges while doing this project.

ABSTRACT

This project focuses on creating and testing a flexible microstrip band stop filter to meet the changing needs of modern wireless communication. Traditional filters can't adjust to different frequency requirements, leading to interference and poor signal quality. To solve this, the project uses advanced components like split ring resonators and varactor diodes, allowing the filter to change its frequency response dynamically. The process starts with designing the filter to operate at 1.5 GHz, using sophisticated simulation tools to model and optimize the design. After the simulations, the filter is physically built on an FR-4 substrate, which has specific thickness and loss properties. The built filter is then tested with a vector network analyser to compare its real performance with the simulated results. This thorough approach of designing, simulating, building, and testing aims to create a highly adaptable and efficient filter. This new filter will be able to adjust to different frequency needs, improving the resilience and performance of communication systems in today's complex frequency environment. The goal is to reduce interference, enhance signal quality, and boost the overall adaptability and efficiency of modern communication systems.

Keywords: *Reconfigurable Filter, Adaptive Frequency tuning, Cognitive Radio, Signal Interference Mitigation, Dynamic Frequency Response.*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

5G	Fifth Generation
ABSF	Absorptive Bandstop Filter
ADS	Advanced Design System
BPF	Bandpass Filter
BSF	Bandstop Filter
CM	Common Mode
CPW	Coplanar Waveguide
CSRR	Complementary Split Ring Resonator
CST	Computer Simulation Technology
DGS	Defected Ground Structure
DMLR	Dual-Mode Loop Resonator
EBG	Electromagnetic Bandgap
EW	Electronic Warfare
FBW	Fractional Bandwidth
FIR	Finite Impulse Response
FPMS	Field-Programmable Microwave Substrates
FR-4	Flame Retardant 4
GSM	Global System for Mobile Communications
HFSS	High-Frequency Structure Simulator
HPF	High-Pass Filter
MCLIN	Microstrip Coupler Line
MEMS	Micro-Electro-Mechanical Systems
MLIN	Microstrip Line
mmWave	Millimeter Wave
MIMO	Multiple Input Multiple Output
MSTRUB	Microstrip Stub

MSUB	Microstrip Substrate
mMTC	Massive Machine-Type Communications
PCB	Printed Circuit Board
PIN Diode	Positive-Intrinsic-Negative Diode
Q-Factor	Quality Factor
RF	Radio Frequency
S-Param	Scattering Parameter
S(1,1)	Input Reflection Coefficient
S(2,1)	Forward Transmission Gain
SIW	Substrate-Integrated Waveguide
SIR	Step Impedance Resonator
SPDT	Single Pole Double Throw
SRR	Split Ring Resonator
TL	Transmission Line
UHF	Ultra High Frequency
VNA	Vector Network Analyzer
WiFi	Wireless Fidelity

CHAPTER -1

INTRODUCTION

1.1 OVERVIEW OF FILTERS IN COMMUNICATION

Filters are indispensable components in both analog and digital communication systems, playing a key role in enhancing the quality of transmitted and received signals. They selectively allow specific frequencies to pass while attenuating others, ensuring that only the desired signal reaches its destination with minimal distortion or interference. This ability to isolate certain frequency bands while suppressing noise makes filters essential in maintaining signal clarity, especially in modern communication systems where data rates and signal fidelity are critical. For instance, in wireless communication, filters prevent overlapping frequency bands from interfering with each other, improving the overall system performance. In audio systems, low-pass filters are commonly used to reduce high-frequency noise, providing a smoother and more pleasant listening experience. Similarly, high-pass filters are essential in applications like voice communications, where eliminating low-frequency hum from power lines or background noise can drastically improve the intelligibility of the message.

Moreover, as communication technologies have evolved, so has the complexity and functionality of filters. In digital communication systems, adaptive filtering techniques are implemented through algorithms that allow real- time adjustments to filter characteristics based on the changing environment. These advancements enable more efficient and effective signal processing, catering to the growing demand for higher data rates and lower latency in modern communication applications.

1.1.1 Evolution of Filters in Communication

The concept of filters in communication dates back to early forms of human interaction, where social norms, cultural practices, and language barriers acted as natural filters that shaped the flow of information. As societies became more complex, these filters evolved with the advent of mass media, were editorial control introduced new layers of filtering. Editorial decisions—often influenced by political, social, or corporate interests—determined what information was disseminated to the public, leading to a one-dimensional flow of information that reflected specific agendas. With the rise of the digital age, filters have taken on a more algorithmic nature, particularly on social media platforms, where content is curated and personalized based on user preferences and behaviors. These algorithmic filters, while providing a tailored user experience, have also created concerns about echo chambers, where users are only exposed to content that aligns with their existing views, limiting exposure to diverse perspectives. This has led to a growing recognition of the need for more transparent and balanced filtering mechanisms that can foster a more informed and engaged public.

At the same time, advancements in artificial intelligence (AI) have introduced sophisticated filtering systems that can detect and moderate harmful content, such as hate speech or misinformation, on digital platforms. AI-driven filters can operate in real time, making them invaluable in scenarios where swift content moderation is necessary. As technologies such as augmented reality (AR) and virtual reality (VR) become more mainstream, the role of filters in shaping digital communication will continue to evolve, presenting new challenges and opportunities for managing information in an increasingly interconnected world.

1.1.2 Overview of Filters

Filters have a profound impact on communication systems, as they not only influence the technical transmission and reception of signals but also affect how messages are interpreted. From the linguistic and cultural barriers in traditional face-to-face communication to the editorial controls in mass media, filters have always played a role in shaping how information is conveyed. Today, digital filters, driven by algorithms and artificial intelligence, allow for the personalization of content, but they also introduce new challenges, such as the creation of echo chambers that reinforce pre-existing beliefs.

As digital communication continues to grow, particularly through social media, these filters are becoming more powerful, affecting everything from user interaction to self-presentation. For example, visual filters on platforms like Instagram and Snapchat not only alter how people look but also influence societal standards of beauty and self-expression. In contrast, AI-based filters are designed to moderate content for safety and compliance with community guidelines, filtering out harmful or offensive material.

These filtering mechanisms are critical in maintaining the integrity and quality of the communication environment, especially as more people rely on digital platforms for social, professional, and educational interactions.

1.1.3 Types of Filters

In communication systems, the application of filters extends beyond just managing frequency components. Each type of filter serves a distinct purpose depending on the system's requirements, and their implementation ensures that the communication channel remains clear and optimized for the intended signal. The growing complexity of communication systems, especially with the increasing demand for higher data rates and greater bandwidth, has led to the development of more sophisticated filters.

A) Low-Pass Filters (LPF)

These filters are crucial in applications where it is necessary to allow low-frequency signals to pass while attenuating high-frequency noise. Low-pass filters are used in baseband processing in communication systems to remove high-frequency interference and smooth out digital signals before transmission.

B) High-Pass Filters (HPF)

These filters are designed to pass high-frequency signals while attenuating lower frequencies, making them essential in communication systems that deal with high-frequency voice or data transmission. High-pass filters can help eliminate low-frequency noise, such as hum from power lines or background sounds, ensuring clearer signal transmission.

C) Band-Pass Filters (BPF)

These filters allow signals within a specific frequency range to pass through while attenuating frequencies outside that range. In radio communication, for example, band-pass filters are used to tune into specific stations while blocking others, ensuring that only the desired frequency is received. Band-pass filters are also critical in cellular networks, where they enable the system to handle multiple communication channels efficiently.

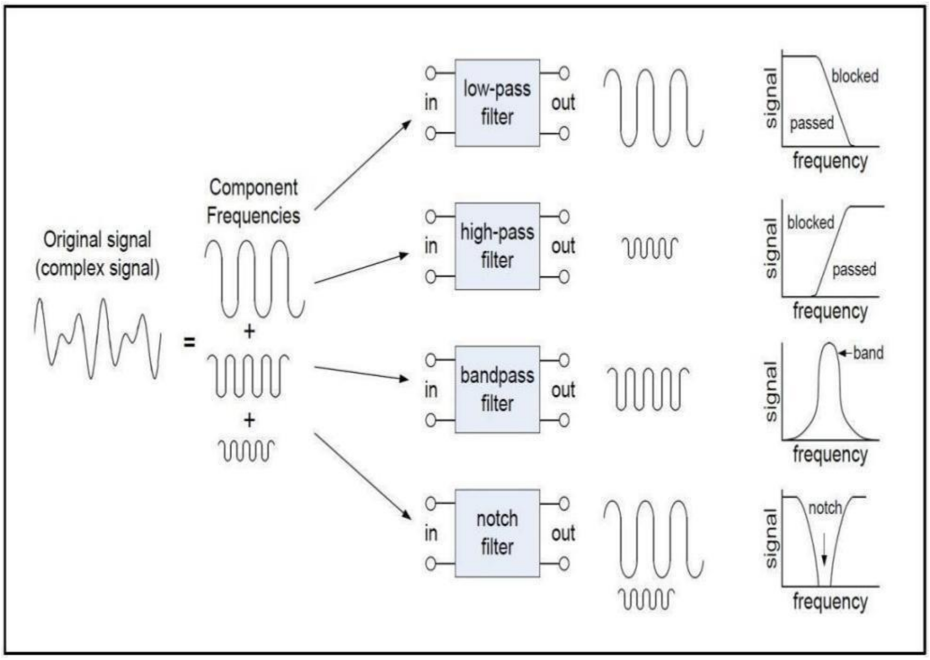

Figure 1.1 Types of Filters

Other advanced filters such as Matched Filters, FIR Filters, and Kalman Filters provide specialized functionalities, ranging from maximizing the signal- to-noise ratio to predicting system states in noisy environments, thus enhancing the overall efficiency of modern communication systems.

1.2 OVERVIEW OF MICROSTRIP FILTERS

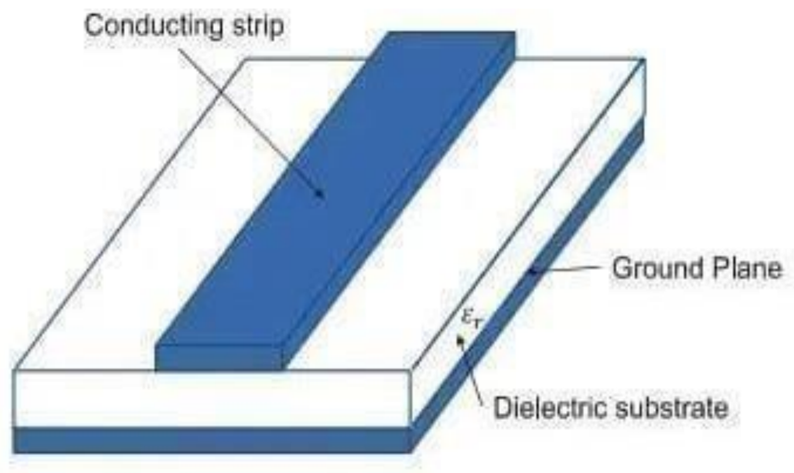

Figure 1.2 Configuration of Microstrip Filter

Micro-Strip filters are an essential component in modern communication systems, particularly in radio frequency (RF) and microwave applications. These filters are designed to selectively filter specific frequency bands while rejecting unwanted signals, thus improving the overall performance of communication systems. micro-strip filters are commonly used in devices such as smartphones, satellite communication systems, radar equipment, and wireless networks due to their small size, lightweight design, and ease of fabrication.

Microstrip filters are built using a dielectric substrate with a conductive strip etched onto its surface, typically made of materials like copper or gold. The dielectric substrate serves as an insulating layer, supporting the conductive strip while influencing the filter's electrical properties. Common materials for substrates include Teflon, FR-4, and Rogers, each offering different dielectric properties that are suitable for specific frequency ranges. The design of microstrip filters is highly flexible, allowing for different configurations such as low-pass, high-pass, band-pass, and band-stop filters, depending on the application requirements.

Microstrip filters are particularly advantageous due to their ability to be fabricated using printed circuit board (PCB) technology, which allows for low-- cost, mass production. This makes them ideal for integration into compact, lightweight devices, especially in high-frequency applications like radar and satellite communications, where space and weight are critical factors.

1.2.1 Basic Structure of Microstrip Filters

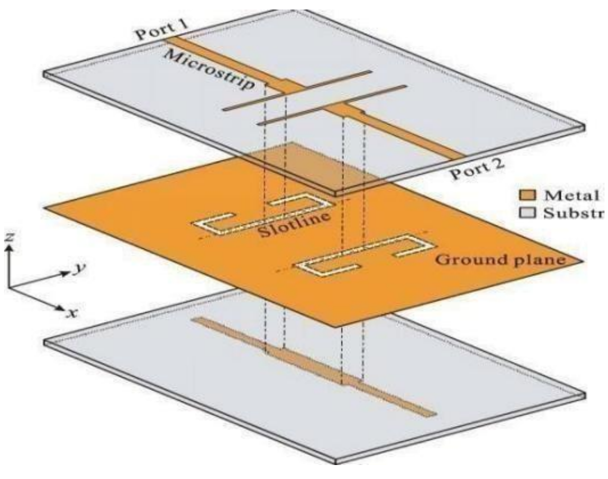

Figure 1.3 Microstrip filter structure

The basic structure of a microstrip filter consists of several key components that work together to provide the desired filtering characteristics in RF and microwave applications. The primary element of a micro-strip filter is a conductive strip etched onto a dielectric substrate. This substrate is typically made of materials with specific dielectric constants, such as Teflon or FR-4, which affect the filter's performance. The conductive strip serves as the signal transmission path, while the dielectric substrate provides electrical insulation and supports the conductive layer. Beneath the dielectric substrate is a ground plane, which plays a crucial role in improving the filter's efficiency by guiding the electromagnetic fields and reducing interference from external sources. The geometry of the conductive strip and the thickness of the substrate are carefully chosen based on the desired frequency response and performance characteristics of the filter. Different topologies, such as stepped-impedance filters, series resonators, and parallel-coupled line filters, are used to achieve specific filtering properties, depending on the application.

1.2.2 Design of Microstrip Filters

The design of microstrip filters involves several key steps to ensure optimal performance for specific applications in RF and microwave communication systems. The first step is to define the specifications of the filter, including the desired frequency range, bandwidth, insertion loss, return loss, and the type of filter (low-pass, high-pass, band-pass, or band-stop). These specifications guide the overall design and selection of components.

Next, the choice of dielectric substrate material is critical, as it affects the filter's performance, including its dielectric constant and loss tangent. Common materials include FR-4, Rogers, and Teflon, each offering different properties that are suitable for specific frequency ranges and environmental conditions. The physical dimensions of the micro-strip line, including its width and length, are then calculated based on the substrate properties and the desired impedance, typically 50 ohms. The filter topology is another important consideration, as it determines the arrangement of the resonators and coupling elements. Popular topologies for microstrip filters include coupled-line filters, which use two or more transmission lines to create band-pass characteristics, and stepped-impedance filters, which alternate sections of different impedances to achieve sharp cutoff characteristics.

1.3 OVERVIEW AND NEED OF RECONFIGURABLE FILTERS

Reconfigurable filters are designed to dynamically adjust their bandwidth, frequency response, or other characteristics in real-time based on system requirements. Unlike traditional filters with fixed properties, Re- configurable filters can operate across multiple frequency bands or modes without the need for physical replacement. This flexibility is particularly valuable in modern communication systems, where devices need to function across various frequency ranges to accommodate multiple standards such as Wi-Fi, 4G, and 5G.

The increasing demand for multi-functional devices and the growing complexity of communication networks have driven the need for Reconfigurable filters. These filters provide a cost-effective solution by eliminating the need for multiple dedicated filters and reducing the size, weight, and power consumption of devices. Re-configurable filters are widely used in applications such as cognitive radios, satellite communication, and military systems, where adaptability and efficiency are critical.

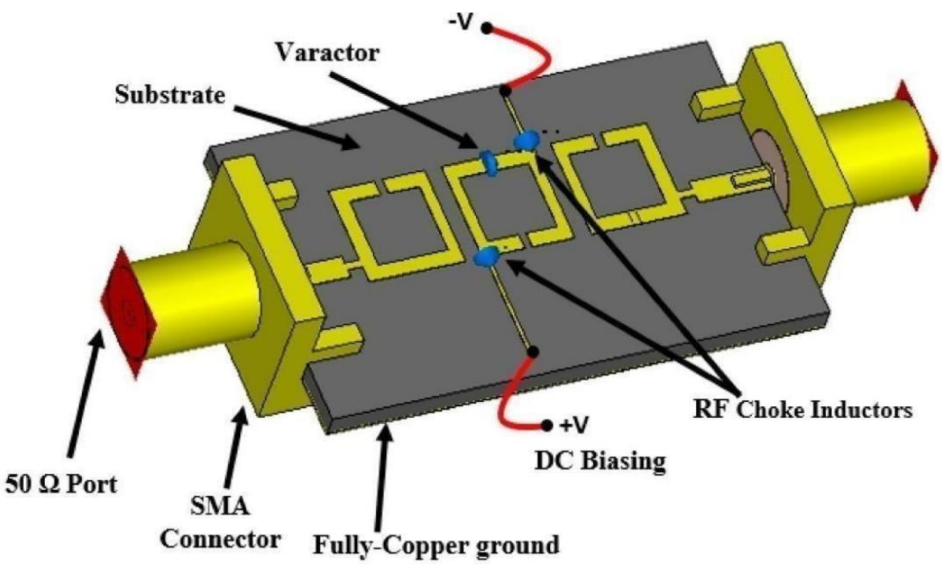

Figure 1.4 Reconfigurable filter structure

1.3.1 Mechanisms of Reconfigurable Filters

Reconfigurable filters achieve their dynamic capabilities through several mechanisms, each suited to different applications and system requirements. Below are the primary mechanisms for reconfiguring filters:

A) Electronic Tuning

Using components like varactors, PIN diodes, and transistors, Reconfigurable filters adjust their frequency response by varying the capacitance or impedance in the circuit. This allows for fast and efficient tuning, ideal for RF and microwave systems.

B) MEMS (Micro-Electro-Mechanical Systems)

MEMS-based filters use tiny mechanical components to modify the filter's structure, allowing for high-precision tuning with minimal power consumption. These filters are commonly used in mobile devices, military systems, and space applications.

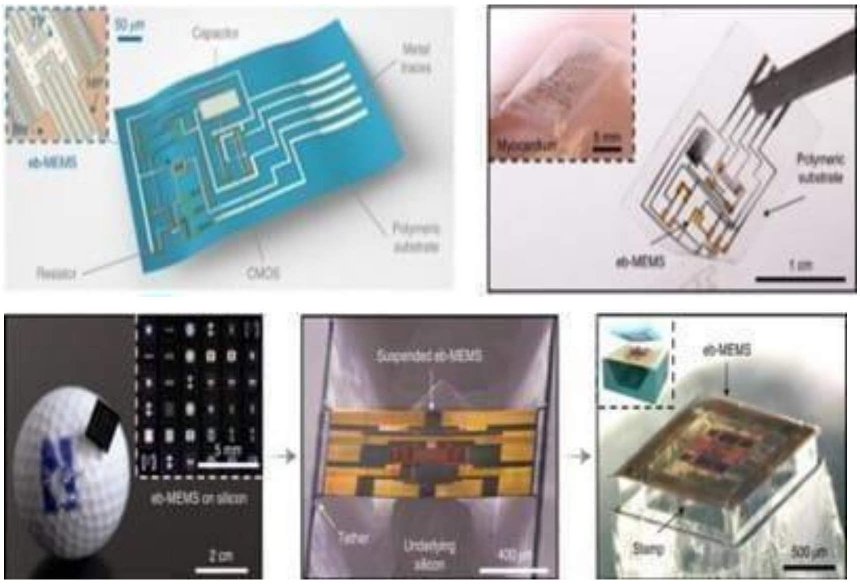

Figure 1.5 MEMS (Micro-Electro-Mechanical Systems)

C) Material-Based Reconfiguration

Materials like ferroelectrics, liquid crystals, and graphene have tunable that change in response to external stimuli such as electric or magnetic fields. This enables smooth, continuous tuning across a wide frequency range, making them ideal for advanced communication systems.

1.3.2 Re-Configurable Microstrip Filters

Re-configurable micro-strip filters combine the compact design of microstrip technology with the flexibility of Reconfigurable components. These filters use conductive strips etched onto a dielectric substrate, with reconfigurability achieved by integrating components like varactors, PIN diodes, or MEMS switches. This allows the filter to dynamically adjust its operating frequency or bandwidth in real-time, making it suitable for applications that require adaptability, such as 5G networks and cognitive radios.

The ability to reconfigure micro-strip filters is particularly important in modern communication systems where devices must operate across multiple frequency bands. By incorporating Re-configurable elements into the design, micro-strip filters can handle the dynamic demands of these systems while maintaining compact size and low power consumption.

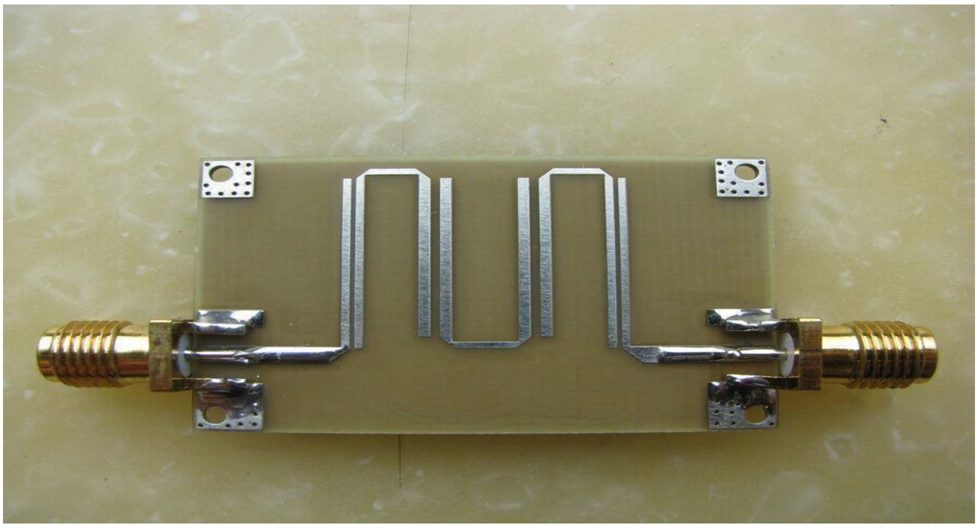

Figure 1.6 Reconfigurable Microstrip filter structure

1.4 DESIGN OF RECONFIGURABLE MICROSTRIP FILTERS

Designing Re-configurable micro-strip filters involves balancing performance characteristics like frequency response, bandwidth, and signal integrity with the ability to dynamically reconfigure the filter based on system requirements. The design process typically includes the following steps:

A) Design Specifications

i. Determine the type of filter, operating frequency range, bandwidth, and impedance matching requirements.

ii. Select Substrate Material: Choose a dielectric substrate material based on the desired frequency range and performance characteristics.

iii. Determine Filter Topology: Select a filter structure, such as parallel-coupled lines or stepped-impedance, depending on the application.

iv. Incorporate Reconfigurability: Integrate components like varactors, PIN diodes, or MEMS switches provide dynamic tuning capabilities.

v. Biasing Network Design: Design a biasing network to control the Re-configurable elements without interfering with the RF signal.

vi. Simulation: Use electromagnetic simulation tools like HFSS or CST to optimize the filter's performance.

vii. Fabrication and Testing: Fabricate the filter on a PCB and test its performance using a Vector Network Analyzer (VNA) to ensure it meets the design specifications.

By following these steps, designers can create effective Re-configurable micro-strip filters that offer the flexibility needed for modern communication systems, ensuring reliable signal processing and minimal interference.

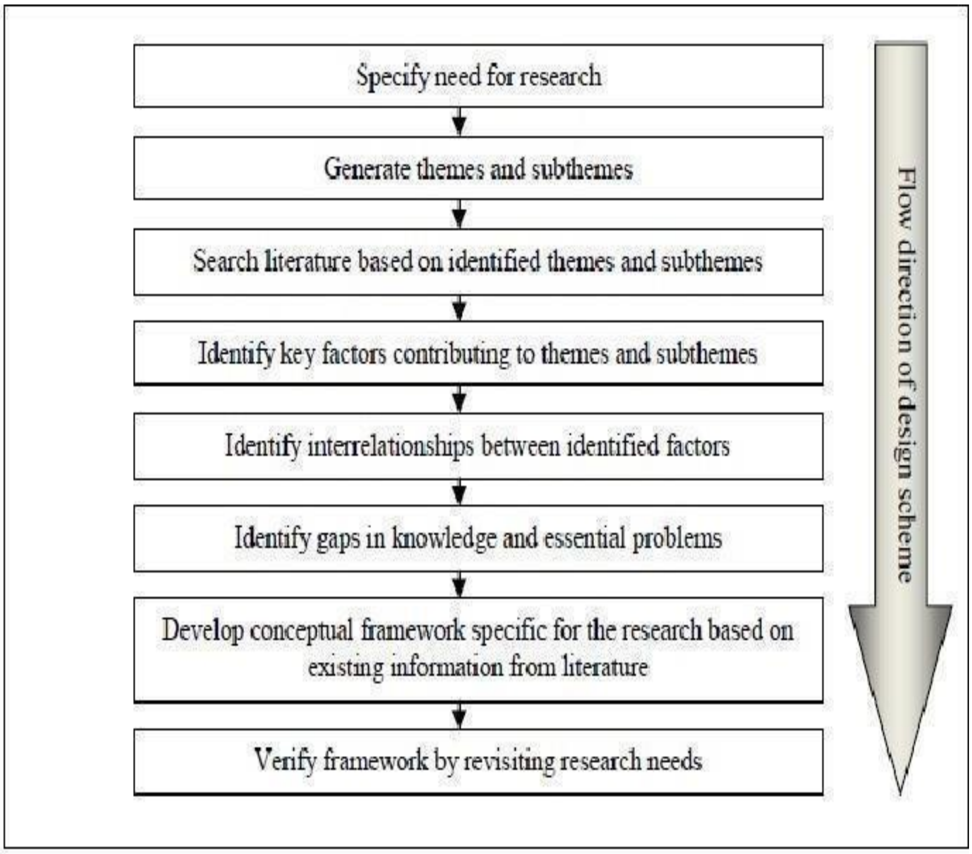

Figure 1.7 Flow-chart of Reconfigurable Microstrip filter

1.4.1 Introduction to Electromagnetic Simulation Software

HFSS (Ansys High-Frequency Structure Simulator) is a leading electromagnetic simulation tool that utilizes finite element analysis for accurate 3D simulations of high-frequency components. Its key features include exceptional handling of complex geometries and multi-layer structures, advanced mesh generation for high accuracy, and support for various analysis types, such as S-parameter extraction. HFSS is particularly well-suited for designing and analyzing antennas, RF components, and integrated circuits.

ADS (Advanced Design System) developed by Keysight Technologies, combines circuit design with electromagnetic simulation, making it an ideal choice for RF and microwave applications. It offers a comprehensive suite of simulation tools for both circuit and electromagnetic design, including filter synthesis and optimization algorithms. The ability to co-simulate between circuit and EM domains enhances its functionality. ADS is widely used in the design of RF amplifiers, mixers, and filters, especially in wireless communication systems.

Sonnet Suites is renowned for its planar EM simulation capabilities, tailored specifically for microstrip and stripline designs. Its high accuracy in simulating planar structures, coupled with efficient processing, makes it a valuable tool. Sonnet supports various RF components and allows for parametric analysis, integrating well with other design tools. It is commonly used for designing RF filters, amplifiers, and other microwave components.

CST Studio Suite is a powerful 3D simulation software that employs different solvers to address a wide range of electromagnetic problems. It features various solvers, including time domain, frequency domain, and static, making it versatile for different applications. CST provides tools for designing and optimizing RF components with detailed visualizations and supports full-wave simulations for complex designs. This tool is frequently utilized in the design of antennas, filters, and high-speed electronics.

1.4.2 Tuning and Testing

Tuning and testing Re-configurable microstrip RF filters are essential for confirming that the design meets performance specifications like reconfigurability, bandwidth, and signal integrity. The tuning process involves using elements such as varactor diodes, PIN diodes, or MEMS switches to adjust the filter's frequency response in real time. Varactor diodes function as variable capacitors influenced by DC bias voltage, while PIN diodes and MEMS switches enable switching between different filter states to access multiple frequency bands. A DC biasing network is crucial for controlling these elements without interfering with the RF signal, using RF chokes and decoupling capacitors to maintain signal integrity.

The tuning steps begin with applying a nominal bias voltage and using a Vector Network Analyzer (VNA) to observe the filter's frequency response. Fine-tuning involves gradual adjustments to achieve the desired performance, including bandwidth and insertion loss, while ensuring smooth transitions between different modes. Once tuning is complete, the testing phase involves S- parameter measurements to assess return loss and insertion loss, ensuring proper impedance matching and minimal signal reflection. Additionally, harmonic distortion, isolation between modes, and power handling capabilities are tested. Environmental tests check performance across varying temperatures, while optional tests like time-domain and shock testing ensure robustness in different conditions.

After the testing, performance validation compares measured results with simulated data from tools like HFSS or CST. Any discrepancies lead to design adjustments, such as tweaking bias voltages or component values. Finally, a comprehensive report documents the tuning mechanisms, test outcomes, and adjustments, confirming the filter's readiness for application. Overall, effective tuning and testing ensure the filter operates reliably and efficiently in real-world scenarios.

1.5 APPLICATION OF RECONFIGURABLE MICROSTRIP RF FILTERS

Re-configurable microstrip RF filters are increasingly becoming vital in modern communication systems due to their ability to dynamically adapt to different frequency bands and signal conditions. This flexibility makes them suitable for a wide range of applications, from wireless communication networks to radar and defense systems. Their compact size, lightweight design, and low power consumption further enhance their suitability for various high-frequency applications. Below are some of the key fields where Re-configurable micro-strip RF filters are extensively applied.

1.5.1 In the Field of Wireless Communication

The wireless communication industry has experienced significant growth, with ever-increasing demand for higher data rates, broader bandwidths, and more efficient spectrum usage. Re-configurable micro-strip RF filters play a crucial role in meeting these demands by enabling devices to operate across multiple frequency bands without the need for multiple, dedicated filters.

A) 5G Networks

In 5G networks, where different frequency bands are used for various services (e.g., sub-6 GHz for mobile data and millimeter waves for ultra-high- speed applications), Re- configurable filters allow seamless transitions between bands, ensuring efficient spectrum utilization. By dynamically adjusting their frequency response, these filters can help manage the congestion in frequency bands and maintain high-speed connectivity, crucial for applications like video streaming, IoT, and autonomous vehicles.

B) Cognitive Radios

Re-configurable filters are also essential in cognitive radios, which can automatically detect available channels in a wireless spectrum and adjust their operation to avoid interference. This adaptability improves spectrum efficiency and enhances the reliability of wireless communication systems in environments with fluctuating frequency availability.

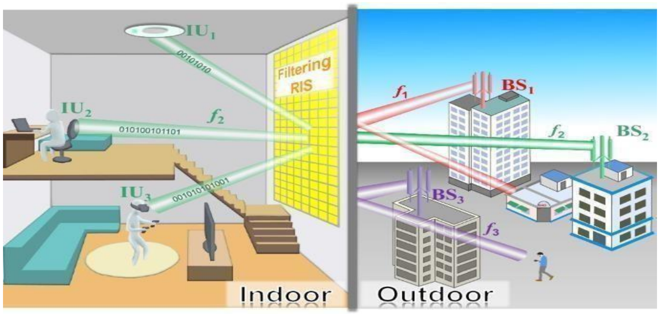

Figure 1.8 Reconfigurable Microstrip in Wireless Communication

1.5.2 Radar and Defense

Radar and defense systems rely heavily on communication technologies that require precision and reliability, especially in dynamic and hostile environments. Reconfigurable micro-strip RF filters offer several advantages in these applications:

A) Military Communication

Military communication systems operate across a wide range of frequency bands to ensure secure and reliable communications in different environments. Re-configurable filters allow these systems to switch between various frequency bands, improving communication resilience while minimizing the risk of interception or jamming. These filters also help reduce the overall size and weight of communication devices, which is critical for field operations where mobility is a key factor.

B) Electronic Warfare (EW)

In electronic warfare, systems must be capable of detecting, analyzing, and countering signals across a broad frequency spectrum. Re-configurable filters provide the necessary flexibility to operate in different frequency bands, allowing defense systems to quickly adapt to new threats or signal environments.

C) Radar Systems

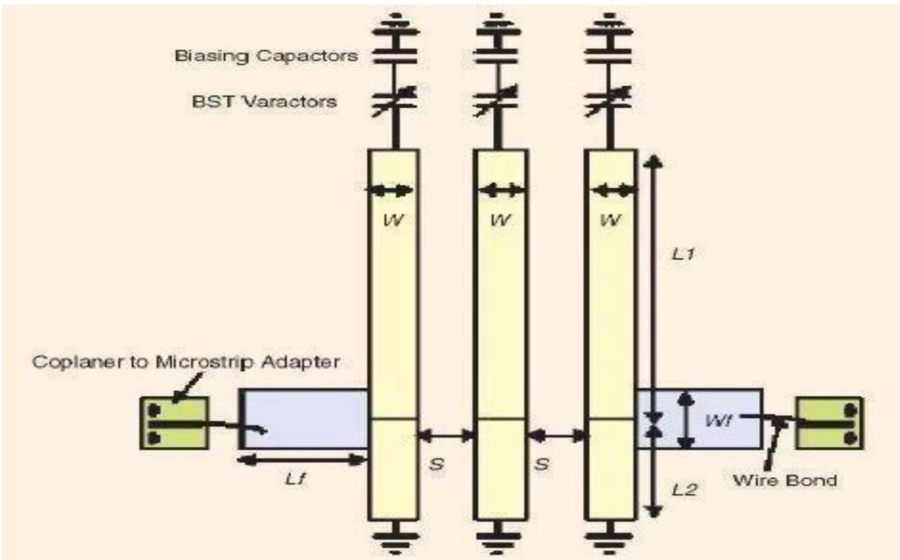

Figure 1.9 Tunable comb Bandpass Filter-Radar application

Modern radar systems operate across multiple frequency bands for applications such as target detection, tracking, and imaging. Re-configurable micro-strip filters enable radar systems to tune across these bands, improving accuracy and resolution by adapting to different operational requirements. This adaptability is particularly valuable in airborne, naval, and land-based radar systems, where environmental factors can affect signal quality and performance.

1.5.2 Other Notable Applications

Beyond wireless communication and defense, Re-configurable micro- strip RF filters have several other notable applications where flexibility and performance are paramount:

A) Satellite Communication

Reconfigurable filters are essential in satellite systems for military applications to combat jamming, avoid interference with terrestrial networks, and switch between frequency bands in multi-band payloads. By minimizing noise and maximizing frequency utilization, they enhance signal clarity in deep space missions, facilitate spectral band switching in Earth observation, and support software-defined radios for flexible communication.

A) Medical Devices

In medical telemetry, reconfigurable filters are utilized in body area networks, wireless implants, and remote monitoring equipment to guarantee dependable data transfer in a variety of settings. With environments including homes, hospitals, and emergency transport, they aid with signal integrity maintenance, interference reduction, and frequency band adaptation.

B) IoT (Internet of Things)

Reconfigurable filters are essential to the proliferation of IoT devices because they enable them to switch between wireless technologies such as Wi-Fi, Bluetooth, and Zigbee based on available spectrum. This flexibility makes IoT networks more dependable and energy-efficient by improving communication efficiency, minimizing interference, and assisting in power consumption reduction.

C) Telecommunication Infrastructure

Cellular base stations with reconfigurable microstrip filters may operate in different bands, supporting 4G, 5G, and other wireless standards without the need for separate filter arrays. This raises service reliability, lowers infrastructure costs, and increases network efficiency. They are crucial to the development of contemporary RF and microwave communication systems because of their adaptability and performance, which are revolutionizing industries.

1.6 CHALLENGES AND LIMITATIONS

While Re-configurable micro-strip RF filters offer significant advantages in flexibility and adaptability for modern communication systems, they also face several challenges and limitations that must be addressed to optimize their performance and usability. These challenges can be categorized into three main areas: challenges in reconfiguration, challenges in manufacturing and materials, and other notable challenges that impact the overall effectiveness of these filters.

1.6.1 Challenges in Reconfiguration

Re-configurable filters must adapt to various operational conditions, but this flexibility introduces several challenges:

A) Speed of Reconfiguration

One of the primary challenges in Re-configurable filters is achieving rapid reconfiguration in real-time applications. The switching speed of components such as varactors, PIN diodes, and MEMS switches can impact the filter's responsiveness, especially in dynamic environments where signal conditions change rapidly. Delays in reconfiguration may result in degraded performance, particularly in applications like cognitive radios or adaptive networks that rely on immediate adjustments.

B) Dynamic Range and Bandwidth

Achieving a wide dynamic range and bandwidth while maintaining performance can be challenging. As Re-configurable filters adapt to different frequencybands, they must ensure that the insertion loss and return loss remain within acceptablelimits. This can be particularly difficult when transitioning between very different frequency ranges, which may require complex adjustments to the filter design and tuning mechanisms.

C) Power Consumption

Although Re-configurable filters are designed to be efficient, the components used for tuning and switching can consume significant power, especially in battery-operated devices. Striking a balance between reconfigurability and power efficiency is critical to ensuring that these filters remain practical for portable and mobile applications.

1.6.2 Challenges in Fabrication and Materials

The manufacturing and material aspects of Reconfigurable micro-strip RF filters present their own set of challenges:

A) Material Limitations

The choice of dielectric materials significantly affects filter performance, including its frequency response, insertion loss, and overall stability. Finding materials that can provide the required dielectric properties while also being cost-effective can be challenging. Additionally, the temperature stability of these materials is crucial for maintaining performance in varying environmental conditions.

B) Fabrication Complexity

The integration of Reconfigurable components (such as MEMS or electronic switches) into micro-strip filters can complicate the manufacturing process. This complexity can lead to increased production costs and longer lead times. Furthermore, ensuring the precise alignment and integration of these components within the filter structure is critical for reliable performance, which may necessitate advanced fabrication techniques.

C) Scalability

As the demand for Reconfigurable filters grows, the ability to scale production while maintaining quality becomes a significant concern. Developing standardized fabrication methods that can accommodate mass production without sacrificing performance or increasing costs is essential for the widespread adoption of Reconfigurable RF filters.

1.6.3 Other Challenges

In addition to the challenges related to reconfiguration and manufacturing, several other factors can limit the effectiveness of Re- configurable microstrip RF filters:

A) Design Complexity

The design of Reconfigurable filters requires advanced modeling and simulation to predict their behavior accurately across multiple frequency bands. This complexity can lead to increased design times and potential inaccuracies if the models do not fully capture real-world behaviors, which may result in filters that do not perform as expected.

B) Interference and Noise

As Reconfigurable filters operate across various frequency band, they may be susceptible to interference and noise from external sources. Ensuring that the filters can maintain performance in noisy environments is critical, particularly for applications such as wireless communication, where signal integrity is paramount.

C) Market Adoption

While the technology for Re-configurable micro-strip RF filters is advancing, market adoption can be slow. Concerns over reliability, performance consistency, and the initial cost of implementing these advanced systems can hinder widespread acceptance in various industries. Educating potential users about the benefits and capabilities of Re-configurable filters is essential for driving adoption.

1.7 FUTURE TRENDS IN RECONFIGURABLE RF FILTERS

As communication technologies continue to evolve, Reconfigurable RF filters are expected to play an increasingly pivotal role in enhancing system performance and adaptability. The following trends highlight the future direction of Re-configurable RF filters, focusing on emerging technologies, advancements in 5G and beyond, integration with antenna systems, and other notable trends.

1.7.1 Emerging Technology

The development of new materials and fabrication techniques is set to revolutionize Reconfigurable RF filters. Innovations such as graphene and two-dimensional materials are being explored for their unique electrical properties, enabling the design of highly efficient and flexible filters. These materials can provide superior performance in terms of speed, weight, and power consumption, making them ideal candidates for next-generation RF filters.

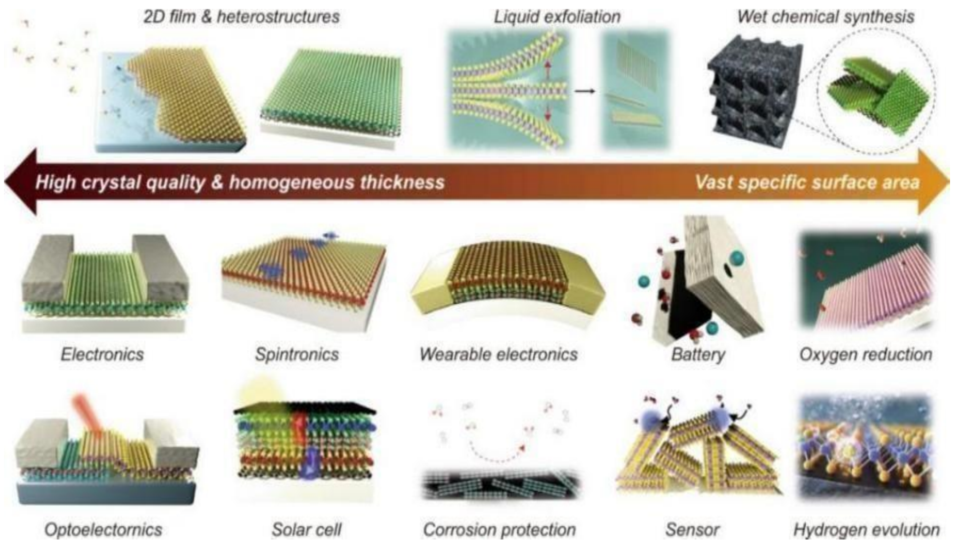

Figure 1.10 Graphene and two-dimensional materials

Additive manufacturing (3D printing) is also gaining traction in the production of RF filters. This technology allows for the creation of complex geometries that are difficult to achieve with traditional fabrication methods. As 3D printing continues to mature, it may enable the production of customized filters tailored to specific applications, enhancing both performance and versatility.

Incorporating Machine Learning (ML) and Artificial Intelligence (AI) into the design and optimization of Re-configurable RF filters is another emerging trend. By leveraging ML algorithms, engineers can better predict filter performance across different operating conditions and optimize designs for maximum efficiency and adaptability. This approach can significantly reduce design times and improve the accuracy of simulations, leading to more reliable products.

1.7.2 5G & Beyond

The rollout of 5G technology is one of the most significant drivers for the advancement of Re-configurable RF filters. As 5G networks demand higher data rates and greater bandwidth, Re-configurable filters will be essential in managing the increased complexity of frequency allocation. These filters will need to support a diverse range of applications, from enhanced mobile broadband to ultra- reliable low-latency communications (URLLC) and massive machine- type communications (mMTC).

As communication standards continue to evolve beyond 5G, Re- configurable RF filters will be crucial in accommodating the various frequency bands utilized by new technologies. The ability to adapt to these changes will enhance network efficiency and facilitate smoother transitions between different communication standards, ensuring seamless connectivity for users. Additionally, sub-6 GHz and Millimetre-wave (mm Wave) frequencies will become increasingly important in future networks. Re-configurable RF filters will play a vital role in filtering out unwanted signals and ensuring optimal performance across these frequency ranges, particularly in dense urban environments where spectrum congestion is a significant challenge.

1.7.3 Integration with Antenna

The integration of Re-configurable RF filters with antenna systems is expected to be a major trend in future communication technologies. Integrated RF system that combines antennas and filters on a single platform will reduce the size and weight of communication devices, making them more suitable for portable applications.

This integration allows for improved performance and efficiency, as filters can be closely coupled with antennas to minimize losses and enhance signal quality. Furthermore, by embedding Re-configurable filters within antenna structures, it becomes possible to achieve multi-band operation with a single antenna, eliminating the need for multiple discrete components. Advancements in innovative antenna technologies, such as beamforming and MIMO (Multiple Input Multiple Output) systems, will also benefit from using Reconfigurable RF filters. These filters can dynamically adapt to the changing communication environment, optimizing signal paths and improving overall system performance.

A) Antenna reconfiguration

Antennas can be dynamically adjusted in terms of frequency, impedance, radiation pattern, and bandwidth by rearranging components such as resistors, capacitors, inductors, and other passive or active elements. With the help of these tuning components, the antenna's response to changing external factors or application specifications can be modified. An overview of the methods utilized to do antenna reconfiguration using resistors, capacitors, and related parts is shown below:

B) Reconfiguration Based on Capacitors

Varactor diodes, also known as variable capacitors, are a well-liked option for adjusting antenna settings due to their capacitance, which can be changed by varying the reverse bias voltage given to it. Reconfiguration of frequency can be accomplished by dynamically altering the resonant frequency by integrating varactors at key points in an antenna construction (such as in the matching network or between radiating elements).

C) Reconfiguration Based on Inductor

Adjusting the inductance in an antenna circuit can be accomplished with variable inductors (also known as tunable inductors), despite their less usage than varactors because of their smaller size. The antenna's impedance and resonant frequency can be adjusted by varying the inductance. These inductors can be integrated with tunable materials or altered manually.

D) Reconfiguration Based on Resistors

Resistive Loading for Bandwidth Control: By adding losses to the circuit, resistors can be utilised to change an antenna's bandwidth. When a wideband response is more important than high efficiency, this is frequently employed to expand the bandwidth at the expense of some gain decrease, which can be helpful.

E) Switchable Reconfiguration Using PIN Diode

Switching Between Various Antenna Modes: PIN diodes are semiconductors that, depending on their bias, can function as radio frequency switches. It is feasible to switch between several operating modes or frequency bands by positioning PIN diodes at specific points in an antenna design (for example, in between radiating arms or elements). This capability enables antennas to be more adaptable and efficient, supporting a wider range of applications with optimized performance.

F) Reconfigurable beam steering

PIN diodes can be used in phased array antennas to turn on and off certain antenna elements, which can be utilized to guide the radiation pattern in different directions. This is particularly helpful for 5G, radar, and satellite communication applications. By dynamically adjusting the beam direction, these systems can achieve improved signal quality and enhanced coverage, even in complex and rapidly changing environments.

1.7.4 Other Trends

Several trends are shaping the future of Re-configurable RF filters:

A) Miniaturization

The ongoing demand for smaller, more compact devices will drive the miniaturization of RF filters. New design techniques and materials will facilitate the creation of smaller filters without compromising performance, enabling integration into mobile devices and wearables. As applications continue to shrink in size, the need for ultra-miniaturized components will only increase, pushing boundaries in design and material science.

B) Multi-Functionality

Future Re-configurable RF filters are likely to become multi- functional, combining filtering, amplification, and other processing capabilities into a single component. This will streamline the design of communication systems and reduce the number of discrete components required. Integrating multiple functions will also enhance overall system efficiency and performance, catering to the evolving requirements of advanced communication networks.

C) Increased Automation

As the design and manufacturing processes become more automated, the production of Re-configurable RF filters will become more efficient. Automated design tools that incorporate AI and ML will enable rapid prototyping and optimization, allowing engineers to quickly iterate on designs and adapt to changing market needs. Furthermore, these intelligent systems will predict performance issues and suggest improvements, speeding up development cycles and reducing costs.

D) Environmental Resilience

With the growing need for communication systems to operate in diverse environmental conditions, future Re-configurable RF filters will need to exhibit increased resilience to temperature variations, humidity, and other external factors. Research into new materials and designs will focus on enhancing the durability and reliability of these filters in challenging environments. This emphasis on resilience is critical for applications ranging from space exploration to harsh industrial environments, ensuring consistent performance regardless of external stresses.

In summary, the future of Re-configurable RF filters is bright, with numerous trends and advancements set to enhance their capabilities and applications. By addressing the challenges of modern communication systems and leveraging emerging technologies, Re-configurable filters will continue to play a crucial role in shaping the future of wireless communication.

1.8 PROBLEM STATEMENT

To reduce interference and improve signal quality, flexible filtering solutions are required due to the quick development of wireless communication and radio frequency technology. The flexibility needed to adapt to dynamically shifting frequency requirements is not present in conventional filters. A reconfigurable microstrip bandstop filter that can dynamically adjust its frequency response has been devised and tested to overcome this difficulty. This novel filter improves communication systems' efficiency and adaptability by utilizing simulation approaches and integrating cutting- edge components, guaranteeing effective operation in a frequency spectrum that is becoming more complex.

1.9 OBJECTIVE OF THE PROJECT

i. To develop an adaptive reconfigurable microstrip RF filter capable of dynamically tuning its frequency response.
ii. To meet the evolving needs of agile defense communication systems by incorporating split ring resonators and varactor diodes.

1.10 SCOPE OF THE PROJECT

The goal of this project is to design, develop, and validate an adaptive reconfigurable microstrip RF filter that can be adjusted dynamically to respond to changing defence communication system requirements for frequency response. This includes integrating varactor diodes and split ring resonators (SRRs) into the filter's design utilizing sophisticated electromagnetic simulation tools for best signal performance and real-time frequency tweaking. The project's main goal is to build a small, high-performing prototype that complies with defense requirements and offers bandwidth optimization, effective interference rejection, and reduced insertion loss. The filter's efficacy in enhancing signal quality and fortifying resistance against interference will be evaluated using simulations and real-world situations. Through the use of cutting-edge components, the project hopes to offer a highly flexible.

1.11 THESIS ORGANISATION

This project focuses on the design and implementation of a reconfigurable microstrip RF filter. Chapter 1 introduces the concept of RF filters and explains the importance of split ring resonators (SRRs) and varactor diodes in constructing adaptive filters capable of dynamic frequency tuning, which is critical for modern wireless communication systems. Chapter 2 presents a literature survey covering various approaches to filter design, highlighting techniques that enhance tunability, reduce insertion loss, and improve overall performance. These studies form the foundation for the design choices made in this project. Chapter 3 details the proposed design, including the configuration of SRRs and varactor diodes, substrate material selection, and simulation using ADS and CST Studio. Chapter 4 discusses the results of simulations and physical tests, providing a comparative analysis to validate the filter's performance. Finally, Chapter 5 summarizes the project's outcomes and proposes future enhancements, such as increasing reconfiguration speed and expanding the filter’s adaptability for 5G and cognitive radio applications.

CHAPTER – 2

LITERATURE SURVEY

2.1 INTRODUCTION

The development of Microstrip Filters has seen significant advancements in recent years, driven by the growing demands for miniaturization, tunability, and enhanced performance in RF communication systems. This literature review focuses on recent innovations, particularly emphasizing a compact and highly selective Microstrip Filter design that integrates advanced features to address the challenges of modern communication systems, including 5G.

The proposed design combines defected ground structures (DGS), complementary split-ring resonators (CSRRs), and interdigitated coupling structures to achieve superior performance across multiple filter types-namely bandstop, highpass, and bandpass filters. The integration of these elements allows for a flexible and compact solution that achieves a reduction in filter size without compromising on key parameters like selectivity and stopband attenuation.

One of the central themes of this review is the exploration of frequency tuning in microstrip filters and its impact on overall filter performance. In particular, the design under consideration offers a bandstop filter operation at 4 GHz, with a highpass cutoff frequency at 6.2 GHz, and a bandpass filter that covers the 3.8 -7.3 GHz frequency range. This frequency agility is critical for modern RF systems, where the ability to dynamically tune the frequency response can mitigate interference and optimize communication channels. As communication systems evolve, the ability to push the boundaries of Microstrip Filter technology will be key to enhancing efficiency and performance in RF applications. Moreover, leveraging materials with high dielectric constants can improve filter miniaturization while maintaining performance, making it suitable for compact, high- frequency communication systems. As RF technologies continue to advance, such innovations in filter design are essential to meet the demands of increasingly complex and dense signal landscapes.

2.2 LITERATURE SURVEY

Salal I. Yahya, et al., [2023], [1] focused on the design and optimization of a compact microstrip filtering coupler for RF communication systems, the work targeted operation within the 1.84 to 2.11 GHz range with a 13.7% bandwidth, suitable for 5G and GSM applications. Coupled lines and microstrip stubs were utilized to develop and optimize two bandpass filters (BPFs) through Advanced Design Systems. The design, modeled with an LC circuit, achieved low insertion losses (0.023 dB and 0.078 dB), a compact size of 19.2 mm × 23.4 mm, and high isolation of -42 dB. Performance was validated through measurements using an HP8757A network analyzer, with results closely matching simulations. The coupler provided a balanced phase, magnitude, and group delay of up to 2.3 ns, proving its suitability for high-performance RF applications. This design approach successfully highlighted the effectiveness of coupled-line and stub configurations for achieving compact, high-performance filtering in RF systems. It underscored the potential of microstrip technology to meet stringent requirements.

Zhibin Zeng, et al., [2019], [2] highlighted the development of a reconfigurable filter using a defective ground structure (DGS) for wideband common-mode suppression in high-speed differential circuits. The design featured three varactor-loaded DGS cells that enabled continuous tuning of the common-mode stopband, covering a frequency range from 1.8 GHz to 8.1 GHz. With a compact layout of 15 mm × 10 mm, the filter achieved efficient common-mode suppression while preserving differential-mode transmission quality. An equivalent circuit model using a coupled LC resonator was employed to streamline the design process, providing a basis for optimization. Full-wave simulations in HFSS and ADS were conducted to validate the filter's performance, and results closely matched experimental measurements, confirming the design's effectiveness. This reconfigurable DGS filter provides a versatile solution for high-speed applications requiring reliable common-mode suppression and differential integrity. As data rates and system complexities increased, such reconfigurable filters played a crucial role in maintaining signal clarity and reducing electromagnetic interference in modern communication.

Mengjie Qin, et al., [2024], [3] developed varactor-diode-based continuously tunable microstrip bandpass filters (BPFs), highlighting their essential role in RF front-ends for wireless communication. These filters operated within the UHF and microwave bands, specifically from 0.55 GHz to 2.7 GHz, and demonstrated flexibility in tuning frequency, bandwidth, and transmission zeros (TZs). Techniques such as switchable resonators and zero-value coupling were employed to enhance the tuning range and improve insertion loss (IL) performance. Emphasis was placed on PCB-based designs for their compactness and cost-effectiveness, with substrate-integrated defected ground structures (SIDGS) effectively used to suppress harmonics up to 9.5 GHz. The paper also addressed future trends, including the move toward multifunctional and scalable filters to meet the growing demands of advanced RF applications. This design approach provided a pathway for developing adaptable and efficient components for modern communication systems.

Leanne Johnson, et al., [2022], [4] presented conventional techniques and developed a novel partially air-filled pedestal resonator and filter, integrated into a printed circuit board (PCB) using micro-machining and thermo-diffusion processes. The design achieved an optimal balance between compactness and high-Q factors by utilizing a Substrate Integrated Waveguide (SIW) topology with air as the propagation medium to reduce dielectric losses. A Q-factor of 285 at 5 GHz was achieved, marking a 53% improvement over fully dielectrically filled counterparts. This design combined the high-Q characteristics of ESIW with the compactness of the pedestal topology. A precise fabrication process involving milling, metallization, and thermo-diffusion bonding enabled the successful realization of both the resonator and a second-order filter. Comparing simulations with experimental results validated the performance, demonstrating the design’s capability to achieve superior electrical characteristics. This breakthrough established a new standard for compact, high-Q RF filters, highlighting the potential of partially air-filled structures to meet the demands of advanced communication systems. The design demonstrated that careful material and process selection could achieve both miniaturization and performance

Roberto Gomez- Garcia, et al., [2018], [5] designed a multi-band RF filtering coupler with dynamically controlled bands to address the needs of modern wireless communications, particularly in 5G systems. The study introduced multi-resonant bandpass and bandstop modules, which were inter-coupled using 90°/270° transmission lines, allowing independent tuning of both center frequency and bandwidth. Techniques such as impedance inverters were applied to control bandwidth and coupling mechanisms, enabling flexible power-division ratios and the production of in-phase or out-of-phase output signals. Practical validation was achieved through microstrip prototypes with reconfigurable dual-band pass and stop filters, covering the frequency range of 1.3-1.8 GHz. These filters demonstrated harmonic suppression, tunable bandwidth, and scalability in design. The paper also highlighted potential advancements in multi-functional, scalable RF filters to enhance performance in compact and adaptive RF systems.

Mohamed Kheir, et al., [(2017], [6] introduced a highly miniaturized class of reconfigurable ultra-wideband (UWB) filters, designed for multi-band and multi-standard transceiver architectures. This filter was built on a multi-mode ring resonator with variable section impedance, providing tunability across the bandwidth, center frequency, and bandnotch frequency. Techniques such as varactor and PIN diodes enabled a high degree of tuning flexibility. The filter achieved a fractional bandwidth exceeding 119%, effectively covering the entire UWB range from 3.36 GHz to 10.53 GHz while maintaining low insertion loss. Analytical models, including transmission line methods (TLM), were applied for precise performance predictions, with simulations showing strong alignment with experimental results. The compact design and cost-effective PCB implementation made this filter an ideal candidate for modern wireless systems, addressing the need for adaptable, high-performance filtering in compact transceivers. The close agreement between simulated and experimental results confirmed the design’s reliability, setting a solid foundation for further development in UWB reconfigurable filter technologies. Its success reinforced the value of integrating tuning elements like varactors and PIN diodes in achieving adaptable, high-performance filtering.

Mohammed R. A. Nasser, et al., [2023], [7] explored a tunable band-pass filter (BPF) design that achieved ultra-wide center frequency tuning from 1.8 GHz to 3.85 GHz, using RF-switched BPFs and a tuning-coupling-less approach for bandwidth tuning ratios up to 3:1. Varactor diodes provided electronic tunability for both frequency and bandwidth, while a multi-layer PCB design reduced the footprint by 43% through vertically stacked filters. A three-pole, two-transmission zero (TZ) configuration with multi-resonant cells, along with quarter-wavelength coupled line resonators (CLRs), ensured enhanced performance. The insertion loss varied between 2-9 dB across tuning states, and high IIP3 levels (12.3 to 30 dBm) enabled robust signal handling. Broadband microstrip-to-microstrip via transitions optimized impedance matching, while the compact vertical filter stack allowed efficient space utilization. The design was experimentally validated for continuous frequency and bandwidth tuning, providing a high performance.

Wei Yang, et al., [2020], [8] proposed a method for achieving precise frequency-selective limiting using absorptive bandstop-to-all-pass filters. Power-activated switching was attained with a reconfigurable threshold between -45 and +8 dBm. High-quality substrate-integrated cavities were employed to enhance performance, achieving a resonator quality factor of 300. Closed-loop feedback provided stable frequency control in varying environments. Out-of-band insertion loss was reduced to less than 0.8 dB, improving overall filter efficiency. The filters were designed with user-prompted overrides, allowing manual mode selection between bandstop and all-pass modes. Power detection ports were integrated to continuously monitor signal levels. The study introduced innovative multi-mode FSL designs featuring both user-defined and power-activated bandstop modes. A measured notch depth of 45-55 dB was achieved over a 1.5-2 GHz tuning range, validating the filter's capability for high-performance frequency-selective limiting. This approach successfully demonstrated the utility of power-activated switching in achieving dynamic frequency-selective limiting, offering adaptable performance across a broad power range. The integration of user overrides and continuous power monitoring enhanced control and flexibility, allowing precise filter adjustments as needed. New standard for efficient and flexible frequency-selective limiting in advanced RF applications.

Shuang Li, et al., [2024], [9] presented a fully tunable bandpass filter (BPF) using cascaded low-pass and high-pass filters, achieving a wide bandwidth tuning range from0.25 GHz to 2.69 GHz by adjusting the cutoff frequencies of the LPF and HPF. Switchable single, dual, and all-off modes were implemented through a notch filter controlled by PIN diodes. A 7th-order quasi-elliptic filter design improved roll-off rates and achieved stopband rejection levels above 30 dB. The center frequency was tuned from 2.9 GHz to 4.6 GHz while maintaining a 1 GHz bandwidth. Selectivity was enhanced using transmission zeros to optimize filter performance. The filter was fabricated on Rogers 5880 substrate. Minimal insertion loss was maintained between 1.45 dB and 3.8 dB across the tuning range, with high return loss (>10 dB) in all operational modes. Three operational modes provided versatility, making the filter suitable for carrier aggregation scenarios. The integration of PIN diodes for mode switching ensured dynamic operation, while the quasi-elliptic design improved overall efficiency. With minimal insertion loss and high return loss, the filter maintained stable performance across its wide tuning range. The versatility and high performance made it a promising solution for multi-band communication systems.

Michael D. Sinanis, et al., [2022], [10] proposed a high-Q, high-power tunable bandpass filter designed for mass production using injection molding technology, catering to the needs of 5G small cell stations. The filter used a tunable evanescent-mode cavity resonator with an acrylonitrile-butadiene-styrene (ABS) thermoplastic polymer. It offered frequency tuning between 2.8–5.2 GHz, achieving an 86% tuning range with an unloaded quality factor (Qu) ranging from 1548 to 2573 and a minimal insertion loss of 0.06–0.1 dB. The implementation demonstrated exceptional power handling of over 100 W. The design integrated a commercial microactuator for precise tuning and ensures scalable, low-cost manufacturing while maintaining superior performance. The technology presented a breakthrough for cost-effective, high-performance tunable filters, particularly in sub-6 GHz 5G applications. The innovative approach paved the way for enhanced adaptability in communication systems. It significantly contributed to the evolution of high-performance RF filter technologies.

Photos Vryonides, et al., [2024], [11] implemented a high-selectivity bandpass filter (BPF) with constant bandwidth and a tunable bandwidth version. The design achieved superior selectivity using open-/short-circuited coupled-line segments at the input and output ports, and symmetrical parallel-coupled lines connected to open stepped-impedance resonators (SIRs). The tunable version employs varactor diodes to adjust the bandwidth, allowing a tuning range from 12% to 60% in the passband. Two prototypes were designed and tested: Filter A covers 2-4 GHz with 60% bandwidth, and Filter B varies bandwidth with a 3-dB FBW from 12% to 60%. Filter A has an insertion loss below 0.8 dB, and Filter B below 1.1 dB. Both filters demonstrated compact size, high selectivity, and an upper stopband suppression level exceeding 40 dB. The design demonstrated effective bandwidth tuning and high selectivity, making it suitable for dynamic RF applications. The use of varactor diodes allowed precise adjustment of the filter's bandwidth, ensuring versatile operation across a wide range.

Qingxin Guo, et al., [2019], [12] developed a tunable bandpass filter using a reconfigurable frequency selective surface (RFSS) with varactor diodes to dynamically adjust the passband. The RFSS is designed with a cross-loop slot, modeled by both parallel and series L-C resonant circuits, enabling independent tuning of the passband and transmission zero. By varying the capacitance from 0.1 pF to 0.8 pF, the passband is reconfigurable between 2.92 GHz and 5.74 GHz. The design includes a DC bias network for the varactor diodes, allowing for voltage control, while resistors are added to reduce interference. A prototype was fabricated using PCB technology, and tests showed that the passband shifted from 4.66 GHz to 2.92 GHz as the bias voltage changed from 18V to 4V. Measurements confirmed the simulated results, with minimal discrepancies attributed to fabrication limits. RFSS is suitable for advanced communication systems requiring tunable performance. The findings validated the effectiveness of using varactor diodes in RFSS for dynamic tuning capabilities. This development offered promising solutions for next-generation communication systems with adaptable frequency responses.

Salman Arain, et al., [2021], [13] attained a superior performance in modern communication systems, a reconfigurable bandpass-to-bandstop filter (BPF- BSF) was developed using advanced technologies. The filter employed a novel selective feeding scheme integrated with Single-Pole Double-Throw (SPDT) switches and PIN diodes for dynamic mode switching. The filter uses a square ring resonator and $\lambda g/4$ open-circuited stubs to achieve transformation between bandpass and bandstop states. In bandpass mode, the resonator presented high performance with sharp rejection and wide bandwidth, while in bandstop mode, it achieved excellent stopband rejection. The design operated at a center frequency of 2.4 GHz, offering a 65% bandwidth in bandpass mode and 70% in bandstop mode with a 40 dB rejection rate. These features are ideal for cognitive radio systems, RF diplexers, and congested environments. The design's high stopband rejection and wide bandwidth made it particularly effective in managing interference in dynamic RF environments, proving its value for cognitive radio.

Yu Guo, et al., [2018], [14] developed a high-performance filter, the study presented a compact high-Q configurable quint-band electromagnetic bandgap (EBG) filter, marking a significant step forward in multi-band wireless communication systems. The filter operated across five frequency bands using an EBG substrate and lumped capacitors, with adjustable passband frequencies enabled by external capacitors. It provided superior performance with high selectivity, low insertion loss, and a wide stopband. The quint-band filter worked at frequencies from 1.53 GHz to 3.3 GHz with band-to-band isolation of over 29 dB. It is designed with coplanar waveguide (CPW) technology and offers excellent spurious suppression from 3.36 GHz to 10 GHz. The design is scalable and compact, making it ideal for modern microwave systems requiring multiple frequency bands. The results demonstrated the filter's effectiveness in addressing the challenges of multi-band operation in wireless systems. Its compact design and high performance positioned it as a viable solution for future communication technologies.

Luis Rodrigus, et al., [2020], [15] developed for mobile satellite terminals, reconfigurable filtennas are designed to operate in the Ka-band, specifically at 20 GHz for downlink and 29 GHz for uplink. These filtennas integrated filters directly into the antenna structure, enabling efficient switching between frequency bands. Two types of filters- Edge coupled and Hairpin are used to improve signal isolation and minimize interference between transmitted and received signals. A PIN diode is employed to alter the antenna's resonant frequency, allowing dynamic reconfigurability. The edge-coupled filters offered better bandwidth and gain, while the hairpin filters provided superior isolation between frequency bands. Compact and low-cost, these filtennas enhanced satellite communication systems by combining filtering and antenna functionalities in a single structure. Their integration of filtering and antenna functions into a single, compact design significantly improved system efficiency and reduced overall costs for mobile satellite terminals.

Anil Rajput, et al., [2022], [16] highlighted the importance of reconfigurable filters in modern wireless communication, the work presented a bandstop filter (BSF) design that operated at multiple frequencies, supporting RFID and mobile communication applications. The filter is reconfigurable between single-band and dual-band modes using a PIN diode (BAP70-03), where it offers a bandstop response from 1.70 GHz to 5.74 GHz when the switch is OFF. In the ON state, it provided dual-band operation with stopbands between 1.42 GHz to 1.59 GHz and 4.82 GHz to 5.73 GHz and a passband from 1.96 GHz to 4.56 GHz for mobile communication (3G, 4G, and 5G). Designed using a stub topology and coupled line scheme, the compact structure is optimized through parametric analysis. Simulations and measurements aligned well, and validated performance in terms of impedance matching, frequency isolation, and bandwidth, making it ideal for RFID, ultra-wideband systems, and modern wireless communication applications. The study underscored the effectiveness of reconfigurable filters in enhancing system flexibility and performance in wireless communications. This design offered a promising solution for future developments in multi-frequency applications and advanced wireless standards.

Dimitra Psychogiou, et al., [2018], [17] developed to address interference challenges in modern RF systems, the wide-band bandpass filter operated within a frequency range of 0.7 GHz to 1.1 GHz, designed to suppress dynamic multi-interference. It featured tunable in-band stopbands that allowed independent control over center frequencies and rejection levels and enhanced flexibility for systems like 5G and wide-band radar. The prototype demonstrated two tunable second-order stopbands with adjustable notches centered around 0.81 GHz and 0.92 GHz, which can be dynamically merged or fine-tuned across the bandwidth. The adaptability made the filter highly effective in mitigating interference while ensuring robust, wide-band performance in congested RF environments. The filter's ability to dynamically adjust stopbands and rejection levels proved invaluable in mitigating interference across a wide frequency range. Its performance in real-world tests confirmed its effectiveness for 5G and wide-band radar systems, offering enhanced adaptability to changing signal conditions. The filter's design and performance confirmed its capability.

Hanyue Xu, et al., [2021], [18] implemented to enhance microwave systems, the reconfigurable filter based on field-programmable microwave substrates (FPMS) operated with tunable center frequencies, bandwidths, and filter orders. The design covered a frequency range from 2.0 GHz to 2.5 GHz and showed a bandwidth variability from 4.2% to 12%. It also demonstrated a 23% tuning range in center frequencies based on bias voltages applied to unit cells. The FPMS filter offered an effective solution for size reduction and dynamic control, making it adaptable to various microwave applications. The filter exhibited 9.12 dB insertion loss and achieved frequency reconfigurability through bias voltage adjustments, impacting performance across various tunable ranges. With dual-passband and bandstop configurations, this filter provided significant flexibility for high-frequency RF systems. The findings highlighted the filter's potential to meet the demands of dynamic microwave applications. Its adaptability and performance enhancements positioned it as a critical component in modern RF systems. This advancement represented a significant contribution to the field of reconfigurable microwave technologies.

Qiu- Sheng Shen., et al., [2018], [19] implemented for wideband applications, the reconfigurable filter operated from 2.0 GHz to 2.5 GHz, and offered tunable center frequencies and bandwidths. The fractional bandwidth can vary from 4.2% to 12%, providing flexibility in RF systems. The filter demonstrated a 23% tuning range for center frequencies, adjusted via bias voltage on unit cells, and enabled precise control over signal characteristics. Insertion loss ranged from 1.3 to 4.7 dB, with excellent phase and magnitude balance across the passband. The design supported dynamic frequency reconfiguration, making it ideal for advanced RF and microwave systems requiring adaptive filtering. The results highlighted the filter's ability to optimize performance across various wideband applications. This breakthrough represented a significant step forward in the realm of flexible technologies for today's RF systems. The filter's performance in dynamic frequency reconfiguration showcased its potential for real-time adjustments in high-demand RF applications.

Juan Carlos Melgarejo, et al., [2023], [20] designed a center frequency for Filters A and B across three discrete states. For Filter A, the center frequencies are 10.7 GHz, 10.8 GHz, and 10.9 GHz, with bandwidths ranged from 50 MHz to 200 MHz Filter B operated at slightly higher center frequencies: 11.2 GHz, 11.3 GHz, and 11.4 GHz, with narrower bandwidths between 40 MHz and 100 MHz the reconfigurable diplexer operated across two states, with frequencies centered at 10.832 GHz, 10.982 GHz, and 11.154 GHz in one configuration, optimized for high-power satellite communication applications. The diplexer achieved separation between channels ensured that channel frequencies differ by at least 60 MHz High return losses, exceeded 25 dB, and minimal transmission losses are critical for both filters and the diplexer. Additionally, the devices undergo rigorous high-power analysis to ensure they withstand multifactor and corona effects, crucial for space and ground applications. These performance metrics highlighted the robustness and reliability required for maintaining stable operations in demanding environments.

Hashinur Islam, et al., [2020], [21] highlighted the importance of diode-based reconfigurable microwave filters for cognitive radio applications, the work explored the ability to dynamically adapt across multiple frequency bands. The filters are divided into tunable, switchable, and hybrid types, providing flexibility in frequency and bandwidth reconfiguration. Tunable filters, featured varactor diodes, and covered frequency ranges like 0.98-1.22 GHz and 1.63-1.95 GHz with stable bandwidths. Switchable filters, employing PIN diodes, achieve frequency shifts between bands such as 1.2 GHz and 3.5 GHz. The hybrid filters integrated both diode types, and enabled multimode transformations, with frequencies ranging from 1.25 GHz to 5.2 GHz and bandwidths up to 75%. The filters played a crucial role in cognitive radio systems, ensuring dynamic spectrum. The integration of diode-based reconfigurable filters significantly improved the adaptability and efficiency of cognitive radio systems, allowing for seamless spectrum access across multiple bands. By utilizing varactor diodes in tunable filters and PIN diodes in switchable filters, the design achieved superior performance in dynamic frequency allocation. The hybrid filters, which combined both types of diodes, enhanced the system's flexibility, enabling complex transformations between frequency bands

Muhammad Fasi, et al., [2021], [22] proposed a design of the multi- mode dual-band bandstop filter operated at key frequencies of 1.35 GHz and 2.65 GHz for transmission zeros, with rejection levels improved the order of the coupled line structure increased and reaching 42.66 dB at fourth-order. The coupled line’s impedance values are $Ze = 219\ \Omega$ and $Zo = 68\ \Omega$, with a corresponding electrical length of $\theta = 87.6°$. The structure integrated a step impedance resonator (SIR) to suppress harmonics and improve out-of-band selectivity, optimized at $\sigma = 1.7$. The filter achieved high rejection at the stopbands and generated multiple transmission poles, enhancing performance. Prototypes showed up to nine transmission poles between 0 and 4 GHz with measured return losses greater than 13 dB, making it highly effective for noise suppression in multiband wireless systems. The study demonstrated the filter's capability to significantly improve noise suppression.

Shih- Huan Chien, et al., [2017], [23] featured the wideband absorptive bandstop filter (ABSF) included a stopband centered at 2 GHz with a fractional bandwidth ranging from 12% to 42%. The filter achieved over 60 dB stopband rejection at 2 GHz, with a return loss better than 10 dB from DC to 2.5 times the center frequency. A single resistor is added to absorb input power within the stopband, improving the filter's absorptive capabilities. The design includes quarter-wavelength open stubs, connected by quarter-wavelength lines, and utilizes Chebyshev response with a ripple constant of 0.1005. The filter featured microstrip implementation, with measured power dissipation exceeding 90% in the stopband, and provided efficient harmonic suppression with minimal passband loss. The results highlighted the filter's effectiveness in achieving substantial power absorption and harmonic suppression. This innovation represented a significant contribution to the development of advanced absorptive filtering technologies in RF applications. The filter's design demonstrated excellent performance in suppressing unwanted frequencies while maintaining minimal passband loss.

Ziyang Lu, et al., [2023], [24] designed a wideband absorptive bandstop filter (ABSF) that included a stopband centered at 2 GHz with a fractional bandwidth ranging from 12% to 42%. The filter achieved over 60 dB stopband rejection at 2 GHz, with a return loss better than 10 dB from DC to 2.5 times the center frequency. A single resistor is added to absorb input power within the stopband, improving the filter's absorptive capabilities. The design included quarter-wavelength open stubs, connected by quarter-wavelength lines, and utilized Chebyshev response with a ripple constant of 0.1005. The filter featured microstrip implementation, with measured power dissipation exceeding 90% in the stopband, and provided efficient harmonic suppression with minimal passband loss. Additionally, the design ensured excellent selectivity with sharp rejection at the stopband edges, and its optimized structure minimized size without compromising performance. The filter is highly effective for applications requiring wideband absorption and noise suppression across a broad frequency range. Thermal analysis confirmed the filter's stability under high power conditions

Ali Kursad Gorur, et al., [2024], [25] explored a single-/dual-band frequency-tunable bandpass-to-bandstop filter. Offered reconfigurability between bandpass and bandstop modes using dual-mode loop resonators (DMLRs). The filter employed SPDT switches to toggle between modes, while center frequency tunability is achieved through the integration of varactor diodes in the DMLRs. The single-band filter demonstrated tuning in the bandpass mode from 1.65 GHz to 1.96 GHz, and from 1.68 GHz to 1.93 GHz in the bandstop mode. For the dual-band filter, the first passband operated between 1.38 GHz and 1.53 GHz, and the second passband between 1.82 GHz and 2.08 GHz, with insertion losses ranging from 3.3 to 6.8 dB and 2.2 to 4.7 dB, respectively. In bandstop mode, the first stopband tunes between 1.35 GHz and 1.47 GHz, while the second ranges from 1.75 GHz to 2.01 GHz, maintained a rejection level above 10 dB. The dual-band filter's performance across multiple bands and modes demonstrated its potential for use in advanced RF communication systems, offering improved interference mitigation and bandwidth optimization.

Yu Freeman Tang, et al., [2015], [26] attained efficient performance, direct-coupled cavity bandpass filters with a Chebyshev response were realized using substrate-integrated waveguide (SIW) techniques for high-density integration and cost reduction. The filters were designed on Rogers RT/Duroid 6002 substrate and operated near 24 GHz (K- band) with a bandwidth of 440 MHz (1.8%). Three four-pole filters with asymmetric iris and bifurcation-type discontinuities were developed. The insertion loss of the filters was measured at 3.4 dB, 4.0 dB, and 4.9 dB, respectively, due to the high tangent loss of the material. Return loss was measured at 17 dB across the entire passband. The performance is expected to improve by using high-purity ceramic materials with lower tangent loss. Increased substrate thickness may also reduce loss, although it could negatively affect the transition performance if the thickness exceeded 0.020 inches. The findings indicated that the use of high-purity ceramic materials could enhance filter performance by minimizing losses. This research offered valuable insights into optimizing direct-coupled cavity filters for future high-density applications.

Kai-Ran-Xiang, et al., [2018], [27] featured a compact microstrip bandpass filter designed to efficiently suppress unwanted frequencies by using quarter- and half-wavelength resonators. It operated around 1 GHz and reduced spurious signals by strategically placing transmission zeros, which are controlled by adjusting the length of coupled lines and short-circuited stubs. The design significantly extended the filter's stopband and achieved up to 26.4 dB attenuation for higher frequencies. The use of quarter-wavelength resonators also made the filter 50% smaller than traditional designs. Its structure is highly optimized, offers low insertion loss, and excellent performance in rejecting harmonics. The filter design ensured a compact size while maintaining robust frequency selectivity, making it suitable for RF and microwave applications. The findings underscored the filter's capability to efficiently suppress unwanted frequencies while minimizing size. This advancement represented a notable contribution to the field of compact RF and microwave filtering technologies. This innovation offers significant advantages in modern wireless applications, where space constraints and efficient frequency management are crucial. This compact design provides a highly efficient solution for systems with limited space.

Wei-Chung Weng, et al., [2022], [28] attained a wideband and high selectivity in microstrip bandpass filters is crucial for modern RF applications, and the design achieved it using Taguchi's optimization method alongside a full-wave electromagnetic simulator. The filter operated at 2.45 GHz and featured parallel edge-coupled lines, which created transmission zeros for enhanced selectivity. Fabricated on a Rogers RO 4003C substrate, it has a compact size of 0.25 λg by 0.28 λg. After optimization, the filter demonstrated a 3 dB fractional bandwidth of 55.2%, minimal insertion loss of 0.43 dB, and over 15 dB return loss in the passband. Additionally, it achieved high selectivity with steep skirt characteristics. The excellent agreement between simulated and measured results confirmed the effectiveness of the approach and offered a fast, reliable method. These findings underscored the design's effectiveness in meeting the stringent requirements of modern RF applications. The results positioned this filter as a competitive option in the field of high-performance RF components.

Abdul Basit, et al., [2020], [29] highlighted the small size and ability to handle multiple frequency bands, the triple-band filter is designed for GSM (850 MHz), GPS (1.57 GHz), and Wi-Fi (2.4 GHz) applications. It used three quarter-wave resonators, with each one controlled a different frequency band. The first resonator directly controls the GSM band and helps to manage the other two. Adjusted the connections between the resonators, unwanted signals are blocked, improved the filter's selectivity. The design folds the resonators and connects them through a small metal pin to save space, resulting in a compact size of 22×21 mm². It offers 16.84%, 3.5%, and 9.6% bandwidth for the three bands, ensuring great performance in a small package. The results from testing match well with the simulations proving it's ready for use in modern wireless devices. The study confirmed the filter's effectiveness in managing multiple frequency bands while maintaining a compact design. This innovation marked a significant advancement in the development of versatile filters for contemporary wireless applications.

Wentao Yuan, et al., [2019], [30] developed a flexible design for microstrip filters, it introduced a method that achieved bandstop, highpass, and bandpass responses using dumbbell-shaped defected ground structures (DGS), complementary split ring resonators (CSRRs), and interdigitated coupling structures. The design operated effectively across various frequencies: the bandstop filter is centered at 4 GHz with a fractional bandwidth (FBW) of 50%, the highpass filter offered a 6.2 GHz cutoff, and the bandpass filter spans from 3.8 GHz to 7.3 GHz with an FBW of 63%. The filters are fabricated on Rogers 4350B substrate, ensuring compact sizes with high selectivity and strong suppression in the stopbands. Open and short stubs allow flexibility in switching between different frequency responses, optimizing both performance and size. Measured results align well with simulations, and validate the proposed method as a compact and efficient solution. The design successfully demonstrated the potential for integrating multiple filter responses into a single structure. This approach paves the way for versatile, high-performance filter solutions in compact spaces, ideal for advanced communication applications. The flexibility of the design makes it highly adaptable for modern RF systems.

Table 2.1- Comparison of Existing system

Ref	Type of Filter	Frequency of operation	Band-width	Insertion loss	Special features
[1]	Adaptive DGS Filter	1.8-8.1 GHz	6.3 GHz (8.1 - 1.8 GHz)	0.9 dB	Varactor-loaded DGS cells for tunable CM suppression
[2]	Varactor-Based Tunable BPF	0.55-2.7GHz	2.15 GHz (2.7 - 0.55 GHz)	1.2 dB	Zero-value coupling for Improved harmonic suppression
[3]	Multi- Band Bandpass and Bandstop Filter	1.3-1.8 GHz	0.5 GHz (1.8 - 1.3 GHz)	1.5 dB	Dynamic band control, harmonic suppression, scalability
[4]	Adaptive UWB Filter	3.36- 10.53GHz	7.17 GHz (10.53 - 3.36 GHz)	0.8 dB	Multi-mode ring resonator
[5]	Compact BPF with ultra-wide Tuning	1.8-3.85GHz	2.05 GHz (3.85 - 1.8 GHz)	2-9 dB	Multi-layer PCB, RF-switched BPFs
[6]	High- Q Pedestal Resonator and Filter	5GHz	53% Q-Factor upgrade	0.06-0.1 dB	Air-filled pedestal resonator, substrate integrate waveguide

2.3 SUMMARY

The literature survey in the report explored a wide range of advancements in Microstrip Filter technology, with a focus on designed compact, high-performance filters for RF communication systems. The studies presented innovative designs, such as filters operating in the 1.84 to 2.11 GHz range with bandwidths of 13.7%, and flexible bandpass filters tuned between 0.55 GHz and 2.7 GHz for UHF and microwave bands. Key advancements included the use of defected ground structures (DGS), complementary split-ring resonators (CSRRs), and interdigitated coupling structures to improve selectivity and size reduction. These filters offered a high degree of tunability, improved harmonic suppression, and low insertion loss, making them suitable for 5G, GSM, and other advanced wireless applications. Additionally, advanced fabrication methods, such as those involving partially air-filled pedestal resonators and multi-resonant bandpass/bandstop modules, further enhanced performance. The convergence of these technologies highlighted the continuous evolution of microstrip filters, positioning them for crucial roles in future multi-standard communication systems.

CHAPTER-3

DESIGN OF RECONFIGURABLE BAND NOTCH FILTER FOR COGNITIVE RADIO IN DEFENSE ELECTROVEIL

3.1 DESIGN OF SINGLE-ELEMENT METAMATERIAL LOADED BAND-NOTCH FILTER

The integration of metamaterials in microwave filter design has gained significant attention due to their ability to manipulate electromagnetic waves in novel ways. The proposed band-notch filter employs a single-element meta-surface structure featuring a split-ring resonator (SRR) on an FR-4 substrate to achieve selective frequency rejection. The SRR introduces a stopband by generating a resonance at a specific frequency, effectively suppressing unwanted signals within the 1 GHz to 12 GHz range. The key objective of this design is to analyse the resonant behaviour of the single-element structure, optimize its electrical and physical parameters, and establish a baseline for multi-element implementations. The filter's performance is evaluated based on notch depth, quality factor, and bandwidth, ensuring efficient suppression of interfering signals while maintaining minimal insertion loss in the passband.

3.1.1 Design Specifications of the Proposed Filter

The proposed meta surface-based band-notch filter is designed using an FR-4 substrate with a thickness of 1.6 mm, ensuring structural stability and efficient performance. A copper layer with a thickness of 1.6 μm is used as the conducting material to achieve low resistive losses and optimal signal propagation. The filter operates with a characteristic impedance of 50 ohms, enabling proper impedance matching in RF circuits. The loss tangent (tan δ) at 0.011 influences the dielectric properties, ensuring controlled electromagnetic behaviour. The design is simulated and analysed using Advanced Design System (ADS) software to validate frequency response and notch characteristics. The detailed design specifications are summarised in Table 3.1.

Table 3.1 Design Specifications of the Proposed Filter

PARTICULARS	SPECIFICATION
Substrate	FR-4 material
Thickness of substrate	1.6 mm
Conducting material	Copper
Conducting material thickness	35 μm
tan δ	0.011
Software used	Advanced Design Software
Characteristic impedance	50 Ω

3.1.2 Configurations of the Proposed Filter

The proposed filter design progresses through multiple stages, starting with the basic bandstop filter and material specification identification. It evolves from single and three-element structures to a six-element metamaterial-loaded band notch filter with varying ground plane configurations. The filter is then restructured to achieve reconfiguration, followed by prototype development. Finally, the design undergoes testing and validation to ensure optimal performance, as shown in Figure 3.1.

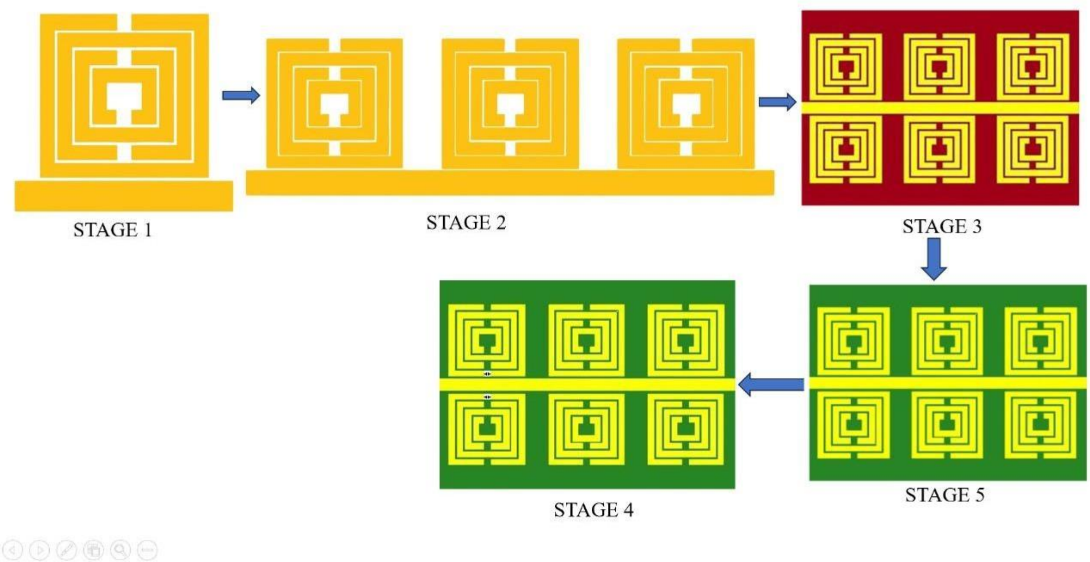

Figure 3.1. Evolution process of the proposed filter design

3.1.3 Design of Single-Element Meta-Material loaded Band-Notch Filter

The proposed single-element metamaterial-loaded band-notch filter goes through different design stages to achieve the desired frequency response. This structure is designed to introduce a notch at a specific frequency, reducing interference while maintaining overall performance. The evolution process of this filter is illustrated in Figure 3.2.

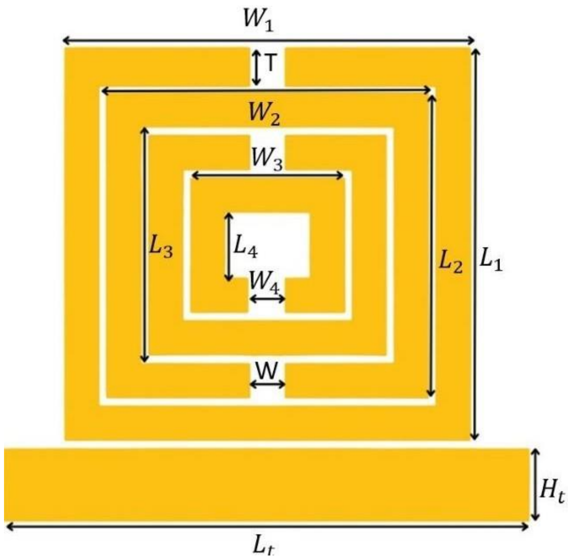

Figure 3.2. Single-Element Meta-Material loaded Band-Notch Filter

Table 3.2 Parameters of Proposed Filter Structure

PARAMETERS	DIMENSIONS
L_1	11
L_2	8.6
L_3	6.2
L_4	3.8
W_1	11.6
W_2	8.2
W_3	4.8
W_4	1.4
T	1
L_t	2
H_t	15

The width and height of the single-element metamaterial loaded band notch filter structure are determined from the following equations (3.1) -(3.4).

$$\frac{W}{h} = \frac{2}{\pi}[B - 1 - ln\, ln\,(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\{ln\, ln\,(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r}\} \quad ... \qquad (3.1)$$

where A and B are calculated as:

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r + 1}{\varepsilon_r - 1}(0.23 + \frac{0.11}{\varepsilon_r}) \qquad ... (3.2)$$

$$B = \frac{377\pi}{2 z_0 \sqrt{\varepsilon_r}} \qquad ... (3.3)$$

The effective dielectric constant (ε_{eff}), which controls signal propagation and field distribution inside the structure, is influenced by the characteristic impedance Z_0. The following provides the effective dielectric constant:

$$\varepsilon_{eff} = \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2}\left(\frac{1}{\sqrt{1 + \frac{12h}{w}}}\right) \qquad ... (3.4)$$

The guided wavelength and phase velocity of the electromagnetic waves are influenced by this parameter. The following formula is used to determine the microstrip length (L) needed to achieve the desired resonance:

$$L = \frac{180^0(\frac{\pi}{180^0})}{\sqrt{\varepsilon_{eff}}K_0} \qquad ... (3.5)$$

where the propagation constant K_0 is given by:

$$K_0 = \frac{(2\pi f)}{c} \qquad ... (3.6)$$

Here, c is the speed of light and f is the operating frequency. Together, these formulas provide the transmission line parameters, guaranteeing ideal impedance matching and resonance behaviour throughout the desired frequency range of 1 GHz to 12 GHz.
These values ensure impedance matching and proper resonance within the 1 GHz–12 GHz frequency range.

3.1.4 Design of Three-Element Meta Material Loaded Band Notch Filter Structure

At this stage of the filter design, a three-element meta-material structure is incorporated to enhance the band-notch characteristics and improve frequency selectivity. This design refines the rejection band by introducing additional resonant elements, allowing for more precise suppression of unwanted frequencies within the designated spectrum. The configuration of the three-element meta-material-loaded band-notch filter is shown in Figure 3.2.

Building upon the single-element structure, this step leverages the interaction between meta-surface elements to enhance the filter's notch performance. The coupled resonant behaviour introduced by the three-element meta-surface improves tunability, ensuring effective frequency rejection while maintaining minimal signal attenuation outside the notch band. This advancement enhances adaptability in cognitive radio applications and interference suppression techniques, making the filter suitable for modern wireless communication systems.

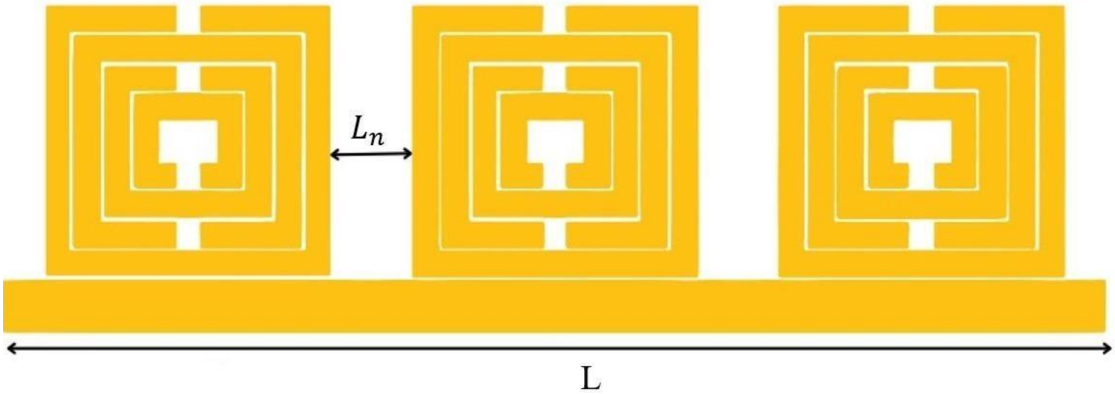

Figure 3.2. Three-element meta-material loaded Band-Notch Filter

3.1.5 Design of Six-Element Meta Material Loaded Band Notch Filter Structure with FGP

At this stage of the filter design, a six-element metamaterial structure is integrated to enhance the band-notch filtering capability while maintaining signal integrity. This structure effectively refines the rejection characteristics by leveraging the interactions between multiple resonators. The configuration of the six-element metamaterial-loaded band-notch filter with a finite ground plane is depicted in Figure 3.3.

The addition of multiple resonating elements allows for sharper attenuation in the stopband and better frequency selectivity. The finite ground plane contributes to the dynamic tuning of the rejection band by altering the capacitance and inductance of the filter structure. This enhances the adaptability of the design, making it suitable for reconfigurable RF applications, such as cognitive radio and interference suppression in wireless communication systems. Electromagnetic simulations validate the improved filtering characteristics of this design, demonstrating enhanced rejection at undesired frequencies while maintaining a stable passband response. The synergy between the six-element metamaterial structure and the finite ground plane provides flexibility for real-world applications, ensuring robustness in dynamic RF environments**.**

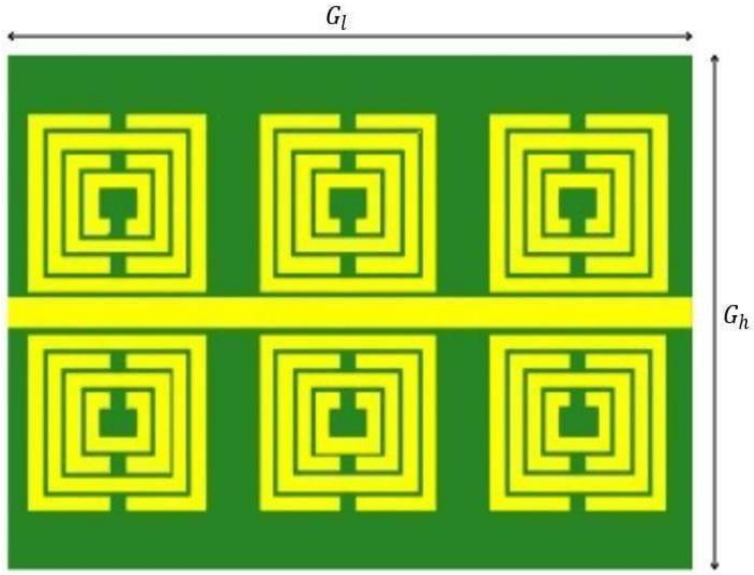

Figure 3.4. Six-element Meta-Material Loaded Band-Notch Filter with Finite Ground Plane

Figure 3.5. Ground Plane structure of Six-element Meta-Material Loaded Band-Notch Filter with finite Ground Plane

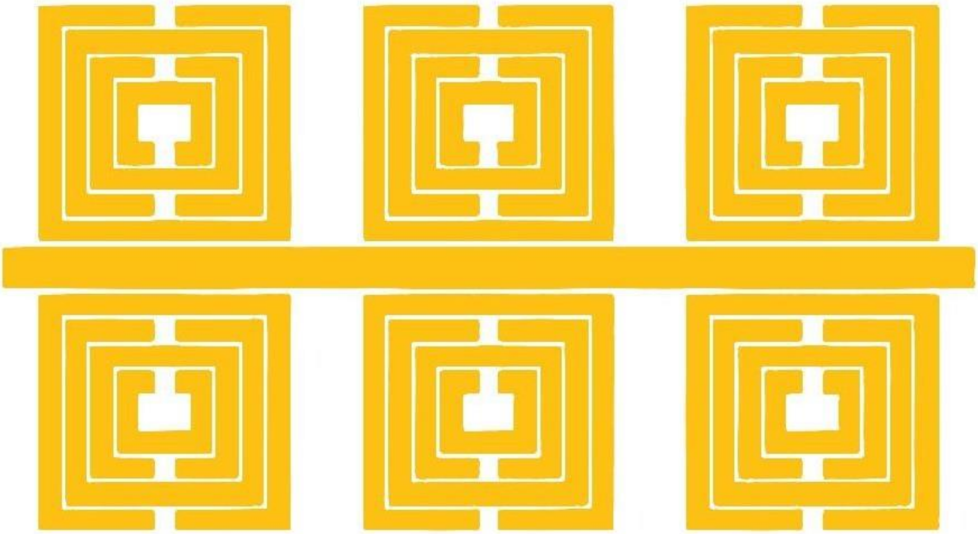

Figure 3.6. Six-element Meta-Material Loaded Band-Notch Filter with finite Ground Plane

3.1.6 Design of Six-Element Meta Material Loaded Band Notch Filter Structure with IFGP

At this stage of the filter design, an infinite ground plane is incorporated into the six-element metamaterial-loaded band-notch filter structure to investigate its impact on frequency rejection characteristics. Unlike the finite ground plane, the infinite ground plane ensures uniform electromagnetic field distribution, reducing radiation leakage and improving filter efficiency. This configuration enhances the band-notch effect by reinforcing the stopband attenuation while maintaining minimal signal distortion. The design layout of the six-element metamaterial-loaded band-notch filter with an infinite ground plane is illustrated in Figure 3.4.

The presence of an infinite ground plane significantly influences surface wave propagation and field confinement, leading to improved resonance stability across the target frequency range. The optimized structure ensures sharper rejection levels while maintaining a consistent transmission response.

Electromagnetic simulations confirm that the infinite ground plane enhances the notch depth and extends the rejection bandwidth, providing better performance in mitigating interference. Compared to the finite ground plane configuration, this design offers improved frequency stability and robustness against environmental variations.

By carefully adjusting the metamaterial structure and its coupling to the ground plane, the band-notch characteristics are further optimized, ensuring efficient signal filtering in practical applications.

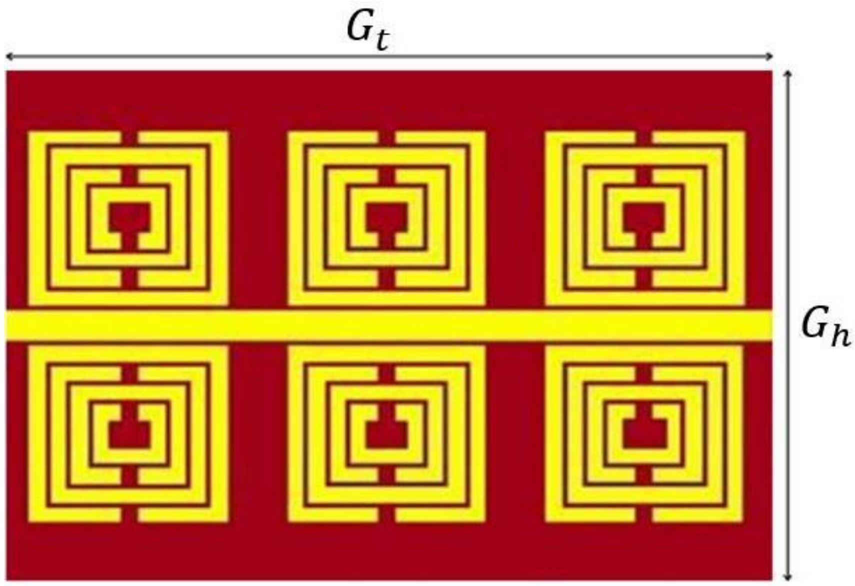

Figure 3.5. Six-element meta-material loaded Band-Notch Filter with infinite ground plane

3.1.7 Six-Element Meta Material Loaded Band Notch Filter Structure with FDGP

At this final stage of the filter design, a capacitor-loaded six-element metamaterial band-notch filter with a finite ground plane is introduced to achieve precise frequency tuning and enhanced filtering performance. The integration of capacitors into the structure allows for dynamic control of the notch frequency, making the filter adaptable to varying signal conditions. The finite ground plane influences the electromagnetic field distribution, affecting the overall performance by introducing controlled resonance variations. The design layout of the six-element metamaterial-loaded band-notch filter with a finite ground plane and capacitor is illustrated in Figure 3.5.

The addition of capacitors plays a critical role in fine-tuning the notch depth and bandwidth, ensuring efficient suppression of unwanted frequency components while maintaining minimal insertion loss. The finite ground plane configuration allows for compact integration without significantly affecting the filter's performance. By strategically placing capacitors within the metamaterial structure, the electrical characteristics of the filter are optimized for enhanced stopband attenuation. This design is particularly suitable for applications requiring adaptive interference mitigation, such as defense communication and cognitive radio systems.

Electromagnetic simulations validate that the capacitor-loaded structure offers superior frequency stability and sharper rejection characteristics compared to previous configurations. The combination of a finite ground plane and capacitive loading enables precise tuning of the resonance frequency, ensuring robust and reliable operation in practical RF applications. By carefully optimizing the capacitor values and placement, the notch filtering response can be dynamically adjusted, making this design highly effective for real-world deployment.

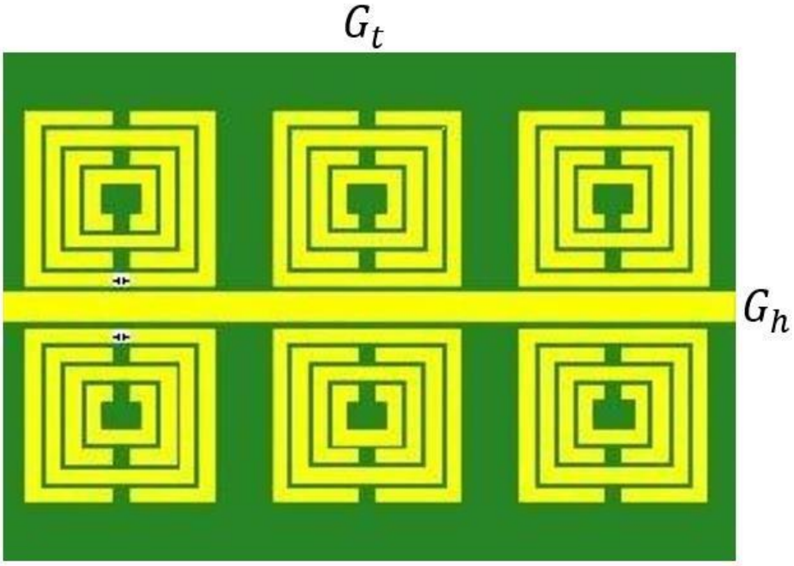

Figure 3.5. Six-element meta-material loaded Band-Notch Filter with a finite ground plane with Capacitor

3.2 INTRODUCTION OF SIMULATION TOOL

The design and analysis of the Six-Element Metamaterial Loaded Band-Notch Filter are conducted using the Advanced Design System (ADS), a state-of-the-art simulation tool widely employed for RF and microwave circuit design. ADS provides an integrated environment for modelling, simulating, and optimizing the filter's performance, enabling efficient prototyping before physical fabrication.

The simulation process starts with defining the geometric structure and material properties of the proposed band-notch filter. The ADS Momentum solver, which is based on the Method of Moments (MoM), is utilized to analyse the electromagnetic behaviour, S-parameters, and frequency response of the filter within the 1 GHz to 12

GHz frequency range. This allows for accurate characterization of the filter's band rejection capability, insertion loss, return loss, and impedance matching.

To achieve reconfigurability, the filter incorporates capacitive loading in the final stage, which enables dynamic tuning of the notch frequency. The use of parametric sweeps and optimization techniques within ADS allows for a detailed analysis of how varying capacitor values (ranging from 1 pF to 5 pF) impact the notch depth and bandwidth. By systematically adjusting the design parameters, the filter’s performance is fine-tuned to achieve optimal interference suppression and signal integrity.

By leveraging ADS for electromagnetic simulations, the proposed reconfigurable band-notch filter is designed to effectively mitigate interference across the 1 GHz to 12 GHz spectrum. The simulation results serve as a crucial validation step before fabrication, ensuring that the filter meets the required performance criteria for real-world RF applications.

3.2 HARDWARE REQUIREMENTS

The implementation of the Six-Element Metamaterial Loaded Band-Notch Filter requires a set of essential hardware components to achieve optimal performance and reconfigurability. The filter is designed on an FR-4 substrate, a widely used dielectric material in RF and microwave applications due to its affordability, ease of fabrication, and stable electrical properties. The choice of FR-4 ensures reliable operation within the 1 GHz to 12 GHz frequency range.

To enable dynamic tuning, capacitors (1-5 pF) are integrated into the last stage of the filter structure. These capacitors play a crucial role in fine-tuning the filter’s notch frequency, allowing for precise rejection of unwanted signals. Their inclusion enhances the adaptability of the filter for reconfigurable RF applications.

For performance evaluation, a Vector Network Analyzer (VNA) is used to measure the S-parameters, return loss, and transmission characteristics of the fabricated filter. The VNA provides accurate assessment of the filter’s notch depth, frequency response, and overall efficiency, ensuring that the design meets the required specifications.

Additionally, ADS is utilized for simulation and optimization before the fabrication stage. This step ensures that the filter performs as expected, minimizing fabrication errors and improving its real-world applicability. By combining precise simulation tools with carefully selected hardware components, the proposed band-notch filter is designed to deliver high performance in RF and wireless communication systems, effectively mitigating interference and enhancing signal quality.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 PERFORMANCE PARAMETER

To reduce interference and improve spectral efficiency, the Reconfigurable Band Notch Filter for Cognitive Radio in Defense Applications is made to modify its frequency response dynamically. With a 20% fractional bandwidth and a centre frequency of 6 GHz, the filter ensures flexibility in real-time electromagnetic situations. With an insertion loss ($S21$) in the passband that is nearly 0 dB and a return loss (s_{11}) that is less than -10 dB, it transmits signals efficiently while ensuring impedance matching and low signal reflection. Varactor diodes are used in the filter to allow for constant notch frequency tuning, which effectively suppresses interference in a variety of bands.

The filter incorporates Split Ring Resonators (SRRs) to improve reconfiguration accuracy and is fabricated on an FR-4 substrate with a dielectric constant (Dielectric constant) of 4.4. It is compatible with common RF systems since it keeps its characteristic impedance at 50 Ω. Advanced revisions of the design include Defected Ground Structures (DGS), which enhance notch performance by expanding the depth and selectivity of rejected frequency bands. The suggested filter is very appropriate for cognitive radio applications in defence communication systems because it integrates these sophisticated tuning techniques to produce effective interference reduction, compactness, and cost-effectiveness.

4.1.1 Return Loss

S_{11}, also known as return loss, is a scattering parameter (S-parameter) that measures the amount of power reflected from the input port of a network due to impedance mismatches. It is expressed in decibels (dB) and is mathematically defined as:

$$s_{11} = 20log\,|\Gamma\,| \qquad \dots (4.1)$$

where Γ (the reflection coefficient) is given by:

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \qquad \dots (4.2)$$

A lower s_{11} value (more negative) indicates better impedance matching, meaning minimal power is reflected and most of the signal is transmitted into the system. For efficient operation, s_{11} should be below -10 dB, ensuring that more than 90% of the power is absorbed by the circuit and less than 10% is reflected. A higher return loss (closer to 0 dB) signifies poor impedance matching, leading to signal reflections, power loss, and reduced system efficiency.

4.1.2 Transmission Loss

Transmission loss refers to the reduction in signal strength as it travels through a system, often caused by impedance mismatches and material losses. It is closely linked to the reflection coefficient, which measures how much of the signal is reflected due to impedance differences between the source and the load. A higher reflection coefficient indicates poor matching, resulting in greater signal loss and reduced transmission efficiency. In RF and microwave systems, minimizing transmission loss is essential for ensuring optimal signal integrity, efficient power transfer, and improved overall system performance. Proper impedance matching techniques help in reducing reflections and enhancing transmission efficiency.

$$s_{21} = -20log\,|\Gamma\,| \qquad \text{... (4.3)}$$

where **Γ** (the reflection coefficient) is given by:

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \qquad \text{... (4.4)}$$

4.2 SINGLE ELEMENT METAMATERIAL LOADED BAND NOTCH FILTER

The simulation and analysis of the Single-Element Metamaterial Loaded Band-Notch Filter provide critical insights into its frequency response and rejection characteristics. This structure serves as the foundational design for achieving selective attenuation within the 1 GHz to 12 GHz range. The introduction of a single metamaterial unit demonstrates a distinct notch at the target frequency, effectively suppressing unwanted signals while maintaining low insertion loss outside the rejection band. The electromagnetic response, analysed using ADS Momentum, highlights the influence of the unit cell geometry and resonant behaviour on the notch depth and bandwidth. The results confirm that the single-element structure exhibits a well-defined resonance, forming the basis for multi-element configurations that enhance reconfigurability and performance. These findings establish the feasibility of metamaterial-based filtering techniques for adaptive RF applications.

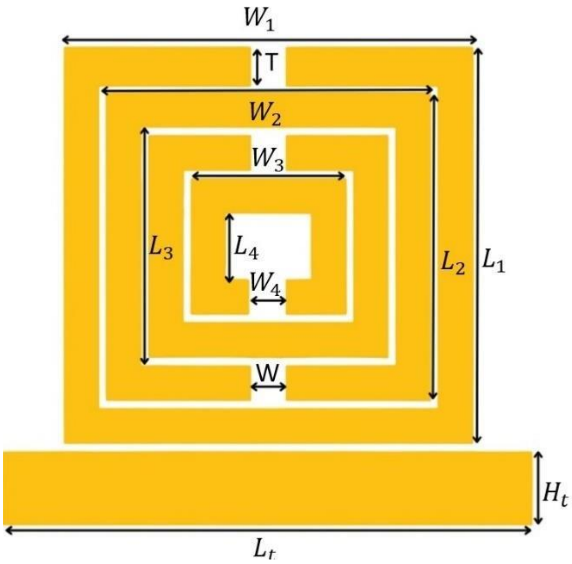

Figure 4.1. Single-Element Meta-Material loaded Band-Notch Filter

4.2.1 Return Loss Characteristics

The S11 parameter, also known as return loss, represents the amount of power reflected to the source due to impedance mismatching. From the graph, it is evident that deep nulls occur at multiple frequencies, indicating strong resonance and minimal reflection at these points. The sharp dips in return loss confirm that the filter is effectively rejecting specific frequencies. The deeper the S11 value (more negative dB), the better the impedance matching at that frequency, minimizing power loss and enhancing filter efficiency.

4.2.2 Transmission Loss Characteristics

The S21 parameter, or transmission coefficient, determines how much of the input signal is transmitted through the filter. The blue dashed curve in the graph illustrates attenuation at certain frequencies, corresponding to the notched bands. These dips signify the suppression of unwanted signals, ensuring that interference is minimized within the rejected frequency range. The smooth transmission in other regions confirms the filter's efficiency in allowing desired signals to propagate with minimal distortion, demonstrating the practical applicability of the design in high-frequency communication systems.

4.2.3 S Parameter Characteristics Graph

The S-parameter characteristics of the proposed metamaterial-loaded band-notch filter are illustrated in the given graph, covering the frequency range of 1–12 GHz. The graph represents S11 (return loss) in red and S21 (transmission loss) in blue dashed lines. The presence of sharp variations in both S11 and S21 curves indicates the resonant frequencies where the filter effectively suppresses unwanted signals. The performance of the filter is evaluated based on these parameters, confirming its ability to selectively reject specific frequency bands while allowing desired signals to pass with minimal attenuation.

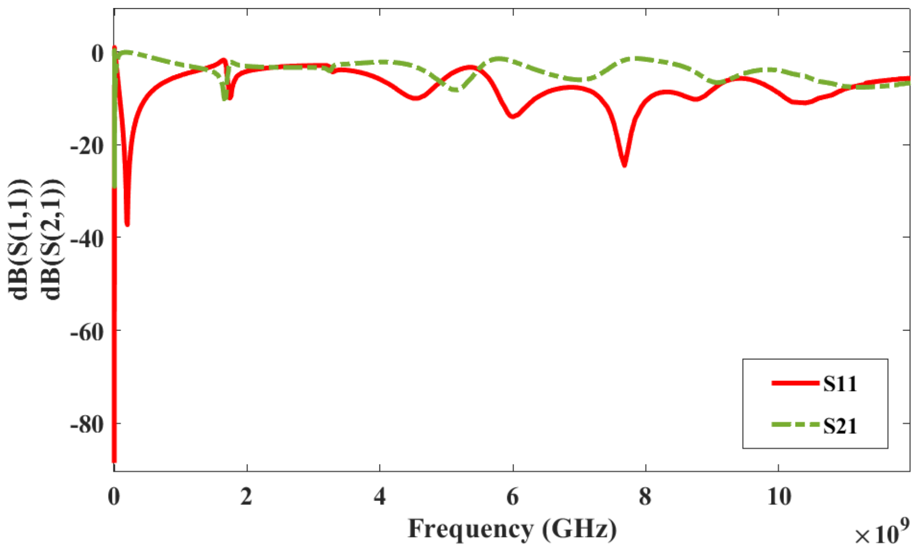

Figure 4.2. S Parameter Characteristics Graph for Single-Element Meta-Material loaded Band-Notch Filter

4.3 THREE-ELEMENT METAMATERIAL LOADED BAND NOTCH FILTER

The three-element metamaterial-loaded band-notch filter exhibits enhanced frequency-selective characteristics, providing improved rejection and sharper notch depths compared to the single-element design. The S-parameter analysis reveals multiple notch bands, demonstrating the filter's capability to attenuate unwanted signals effectively while maintaining low insertion loss in the passband. The increased number of resonant elements contributes to stronger electromagnetic coupling, leading to deeper rejection levels and wider stopbands. This configuration ensures improved filtering performance, making it suitable for advanced communication and radar applications where precise interference suppression is crucial.

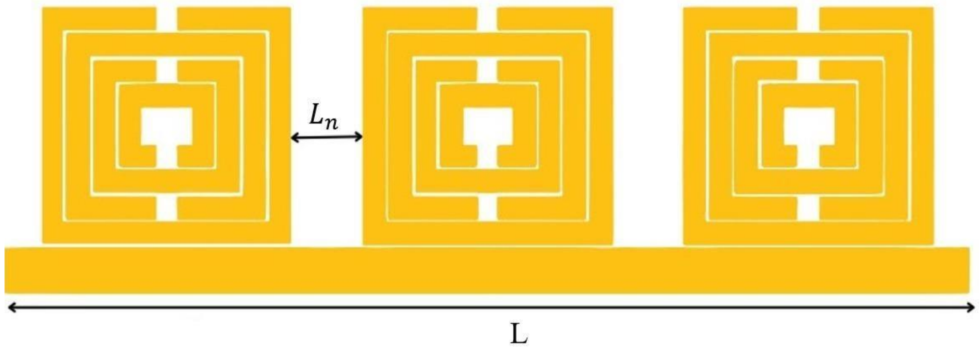

Figure 4.3. Three-element meta-material loaded Band-Notch Filter

4.3.1 Return Loss Characteristics

The S11 parameter, or return loss, represents the amount of power reflected due to impedance mismatches. The graph shows significant dips at multiple frequencies, reaching below -25 dB, indicating excellent impedance matching at these points. This suggests that the filter is effectively minimizing signal reflection and maximizing power transfer. The presence of sharp resonant notches further confirms the precise frequency selectivity of the proposed design, ensuring efficient filtering for targeted applications.

4.3.2 Transmission Loss Characteristics

The S21 parameter, or transmission coefficient, describes how much of the input signal is transmitted through the filter. The blue dashed curve highlights attenuation at specific frequencies, corresponding to the notched bands. These deep dips indicate strong suppression of unwanted signals, validating the filter's role in eliminating interference at targeted frequency bands. In the passband regions, the S21 values remain relatively high, ensuring minimal insertion loss and efficient signal transmission. The overall response confirms that the filter provides effective notch filtering while maintaining a desirable passband performance.

4.3.3 S Parameter Characteristics Graph

The S-parameter graph illustrates the performance of the metamaterial-loaded band-notch filter over the 1–10 GHz frequency range. The S11 (return loss) curve in red and the S21 (transmission loss) curve in blue dashed lines provide insight into the filter's behaviour at various frequencies. The presence of multiple deep nulls in S11 and corresponding dips in S21 indicates the rejection bands where the filter effectively attenuates unwanted signals. These resonant points confirm the filter's ability to suppress interference while ensuring minimal insertion loss in the passband.

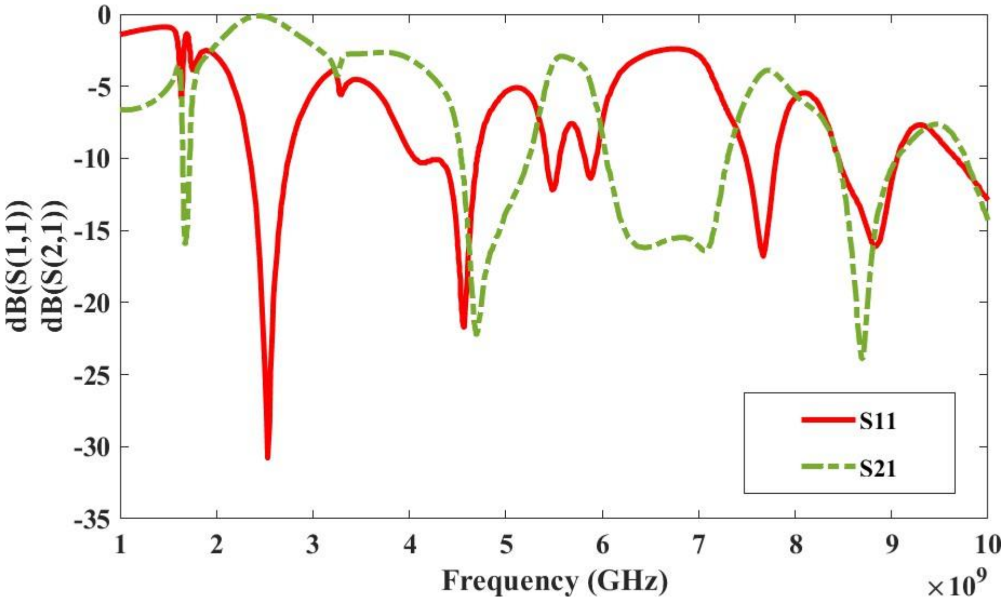

Figure 4.4. S Parameter Characteristics Graph for Three-Element Meta-Material loaded Band-Notch Filter

4.4 SIX-ELEMENT METAMATERIAL LOADED BAND NOTCH FILTER WITH IFGP

The six-element metamaterial-loaded band-notch filter with an infinite ground plane exhibits superior notch depth and enhanced filtering capabilities across the 1–10 GHz frequency range. The S11 parameter indicates multiple deep resonance points, signifying minimal reflection and strong impedance matching at the notch frequencies. The S21 parameter demonstrates effective signal suppression at these frequencies, confirming the filter’s ability to reject unwanted signals efficiently. The presence of six metamaterial elements increases the number of rejection bands and improves selectivity, while the infinite ground plane ensures uniform electromagnetic wave propagation, reducing losses and enhancing overall performance. This configuration is highly effective for applications requiring precise interference mitigation and wideband operation.

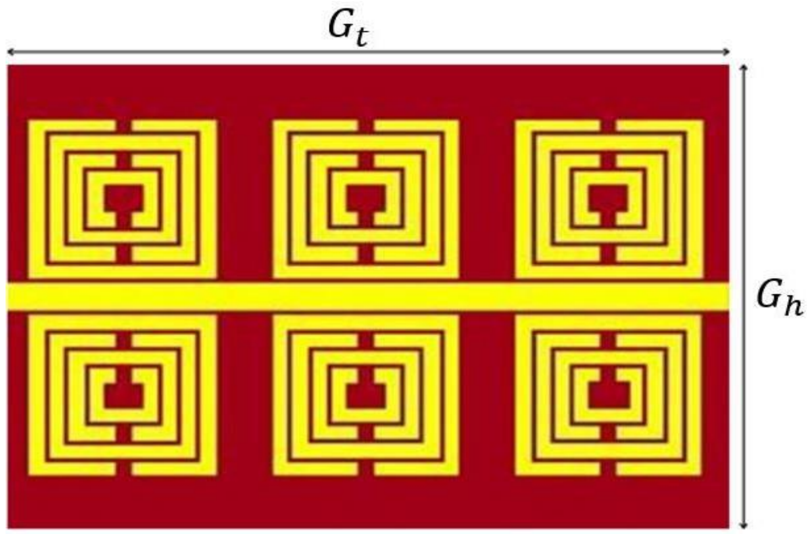

Figure 4.5. Six-element meta-material loaded Band-Notch Filter with infinite ground plane

4.4.1 Return Loss Characteristics

The return loss (S11) characteristics of the metamaterial-loaded band-notch filter exhibit multiple resonances within the 1 GHz to 10 GHz frequency range, as shown in the graph. The deep nulls in the red curve indicate strong impedance matching at specific frequencies, ensuring minimal power reflection at these points. The presence of multiple sharp dips suggests effective absorption of incident signals, leading to improved filter performance. The return loss reaches values below -20 dB at several notched frequencies, confirming the filter’s capability to reject specific bands efficiently while maintaining proper impedance matching outside these regions.

4.4.2 Transmission Loss Characteristics

The transmission loss (S21) response, represented by the blue dashed curve, demonstrates the filter's ability to selectively attenuate signals at targeted frequencies. Significant attenuation can be observed at multiple notch frequencies, where the transmission loss exceeds -10 dB, indicating effective suppression of undesired signals. The presence of multiple stopbands highlights the impact of metamaterial loading, leading to enhanced rejection at key frequency bands. Beyond the notch frequencies, the relatively higher transmission levels suggest minimal insertion loss, ensuring effective signal propagation in the passbands. These characteristics confirm the efficiency of the designed filter in mitigating interference across the operational bandwidth.

4.4.3 S Parameter Characteristics Graph

The S-parameter characteristics of the metamaterial-loaded band-notch filter are depicted in the given graph, showcasing the return loss (S11) and transmission loss (S21) over a frequency range of 1–10 GHz. The return loss (S11), represented by the red curve, indicates how much power is reflected to the source. Several deep notches are observed, demonstrating strong resonance at multiple frequencies, which signifies effective impedance matching at these points. The transmission loss (S21), shown by the blue dashed curve, highlights the attenuation of the signal through the filter. Sharp dips in the S21 curve correspond to the notched frequencies, confirming the filter's ability to suppress unwanted signals effectively. The results validate the filter's performance in selectively attenuating specific frequency bands while maintaining good transmission outside the rejection bands.

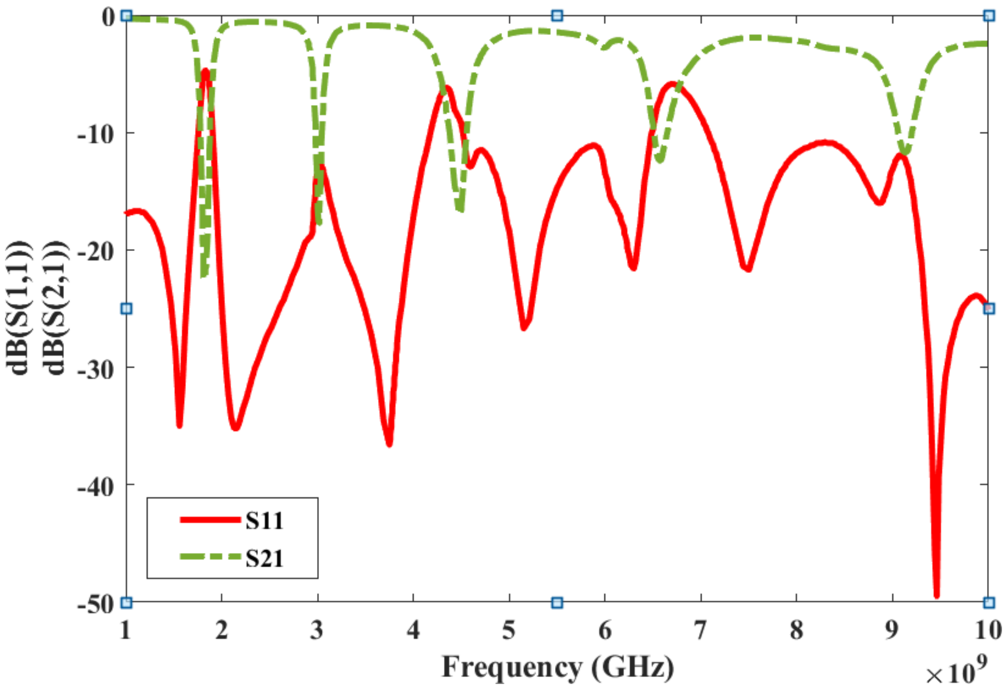

Figure 4.6. S Parameter Characteristics Graph for Six-Element Meta-Material loaded Band-Notch Filter with infinite ground plane

4.5 SIX-ELEMENT METAMATERIAL LOADED BAND NOTCH FILTER WITH FGP

The six-element metamaterial-loaded band-notch filter with a finite ground plane exhibits distinct notch characteristics, providing effective signal rejection across the 1–10 GHz frequency range. The S11 parameter shows well-defined resonance points, indicating strong impedance matching at notch frequencies, while the S21 parameter confirms efficient attenuation of unwanted signals. The finite ground plane influences the electromagnetic field distribution, introducing additional coupling effects that slightly modify the notch depth and bandwidth compared to the infinite ground configuration. This structure is advantageous for practical implementations, as it allows for compact design and integration into real-world microwave circuits, making it suitable for applications requiring selective interference suppression.

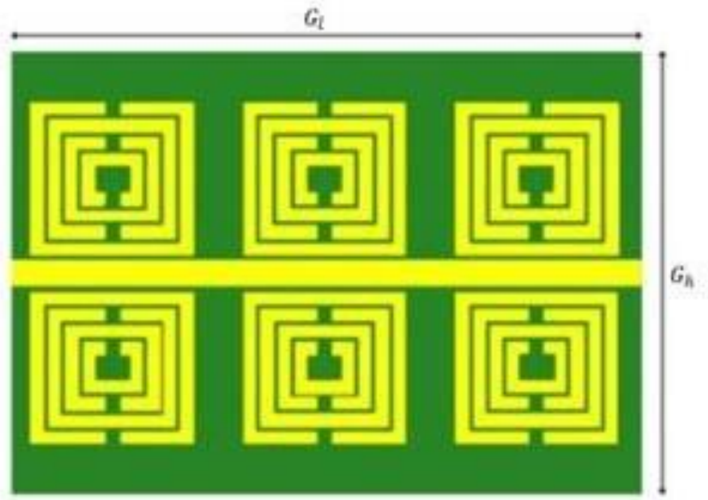

Figure 4.7. Six-element meta-material loaded Band-Notch Filter with finite ground plane

4.5.1 Return Loss Characteristics

The return loss (S11) characteristics of the designed metamaterial-loaded band-notch filter indicate effective impedance matching at passband frequencies, while significant attenuation is observed at the notch frequencies. The deep notches in the S11 curve correspond to high reflection, implying minimal signal transmission at those specific frequencies. The observed return loss values demonstrate the filter's ability to reject unwanted frequency bands efficiently, making it suitable for interference mitigation in RF applications.

4.5.2 Transmission Loss Characteristics

The transmission loss (S21) characteristics reveal strong attenuation at multiple notch frequencies within the 1–10 GHz range. The deep dips in the S21 response indicate the suppression of unwanted signals, confirming the band-notch behavior of the filter. The relatively stable transmission in the passbands ensures minimal signal distortion outside the rejection bands, validating the filter's efficiency in selective frequency suppression.

4.5.3 S Parameter Characteristics Graph

The S-parameter characteristics graph illustrates the overall performance of the designed filter, with S11 representing the reflected power and S21 depicting the transmitted power. The sharp notches in S21 and corresponding peaks in S11 confirm the filter's ability to selectively block specific frequency bands while maintaining good transmission in the passbands. This behaviour ensures optimal performance in communication systems requiring precise frequency filtering.

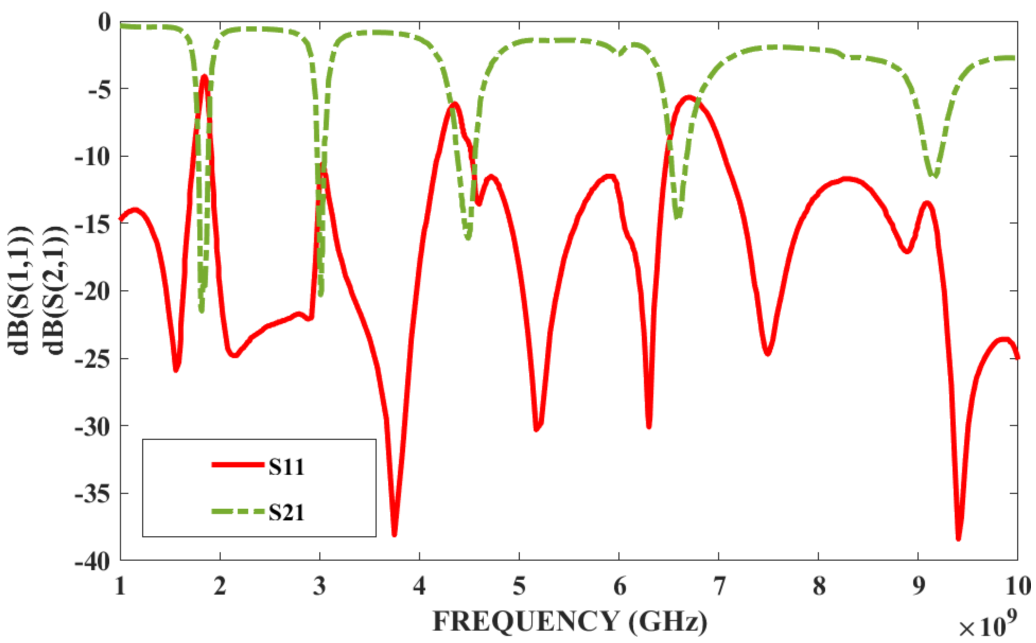

Figure 4.8. S Parameter Characteristics Graph for Six-Element Meta-Material loaded Band-Notch Filter with finite ground plane

4.6 SIX-ELEMENT METAMATERIAL-LOADED BAND-NOTCH FILTER WITH FDGP

The six-element metamaterial-loaded band-notch filter with a finite defected ground plane exhibits superior notch depth and enhanced filtering capabilities across the 1–10 GHz frequency range. The S11 parameter indicates multiple deep resonance points, signifying minimal reflection and strong impedance matching at the notch frequencies. The S21 parameter demonstrates effective signal suppression at these frequencies, confirming the filter’s ability to reject unwanted signals efficiently. The presence of six metamaterial elements increases the number of rejection bands and improves selectivity, while the finite defected ground plane introduces additional resonances and enhances filtering performance. This configuration is highly effective for applications requiring precise interference mitigation and wideband operation.

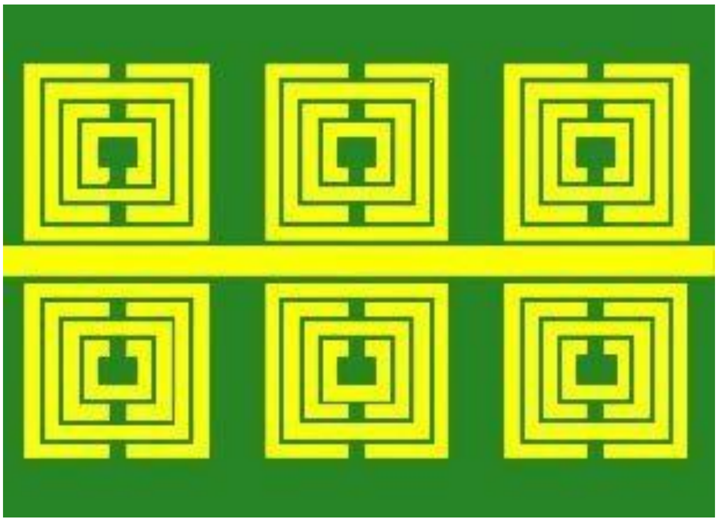

Figure 4.9. Six-Element Metamaterial-Loaded Band-Notch Filter with Finite Defected Ground Plane

4.6.1 Return Loss Characteristics

The return loss (S11) characteristics of the metamaterial-loaded band-notch filter exhibit multiple resonances within the 1 GHz to 12 GHz frequency range, as shown in the graph. The deep nulls in the red curve indicate strong impedance matching at specific frequencies, ensuring minimal power reflection at these points. The presence of multiple sharp dips suggests effective absorption of incident signals, leading to improved filter performance. The return loss reaches values below -20 dB at several notched frequencies, confirming the filter’s capability to reject specific bands efficiently while maintaining proper impedance matching outside these regions.

4.6.2 Transmission Loss Characteristics

The transmission loss (S21) response, represented by the blue dashed curve, demonstrates the filter's ability to selectively attenuate signals at targeted frequencies. Significant attenuation can be observed at multiple notch frequencies, where the transmission loss exceeds -10 dB, indicating effective suppression of undesired signals. The presence of multiple stopbands highlights the impact of metamaterial loading, leading to enhanced rejection at key frequency bands. Beyond the notch frequencies, the relatively higher transmission levels suggest minimal insertion loss, ensuring effective signal propagation in the passbands. These characteristics confirm the efficiency of the designed filter in mitigating interference across the operational bandwidth.

4.6.3 S-Parameter Characteristics Graph

The S-parameter characteristics of the metamaterial-loaded band-notch filter are depicted in the given graph, showcasing the return loss (S11) and transmission loss (S21) over a frequency range of 1–10 GHz. The return loss (S11), represented by the red curve, indicates how much power is reflected to the source. Several deep notches are observed, demonstrating strong resonance at multiple frequencies, which signifies effective impedance matching at these points. The results validate the filter’s performance in selectively attenuating specific frequency bands while maintaining good transmission outside the rejection bands.

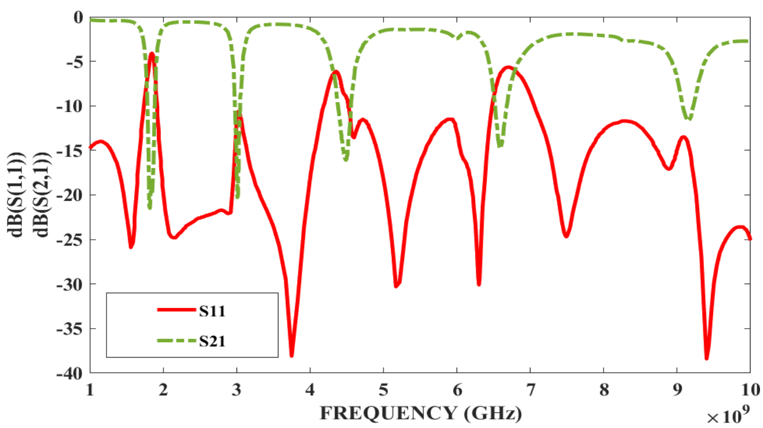

Figure 4.10. S-Parameter Characteristics Graph for Six-Element Metamaterial-Loaded Band-Notch Filter with Finite Defected Ground Plane

4.7 SIX-ELEMENT METAMATERIAL LOADED BAND NOTCH FILTER WITH FGP-C

The six-element metamaterial-loaded band-notch filter with a finite ground plane, integrated with a capacitor, enhances tunability and frequency-selective performance. The inclusion of a capacitor influences the resonance characteristics by altering the effective capacitance of the structure, thereby shifting the notch frequencies within the 1–10 GHz range. The S11 parameter demonstrates strong impedance matching at specific notch points, while the S21 parameter indicates effective attenuation of unwanted signals, showcasing the filter's efficiency. The finite ground plane, combined with the capacitor, introduces additional control over the bandwidth and depth of the notch, making the design highly adaptable for reconfigurable RF and microwave applications.

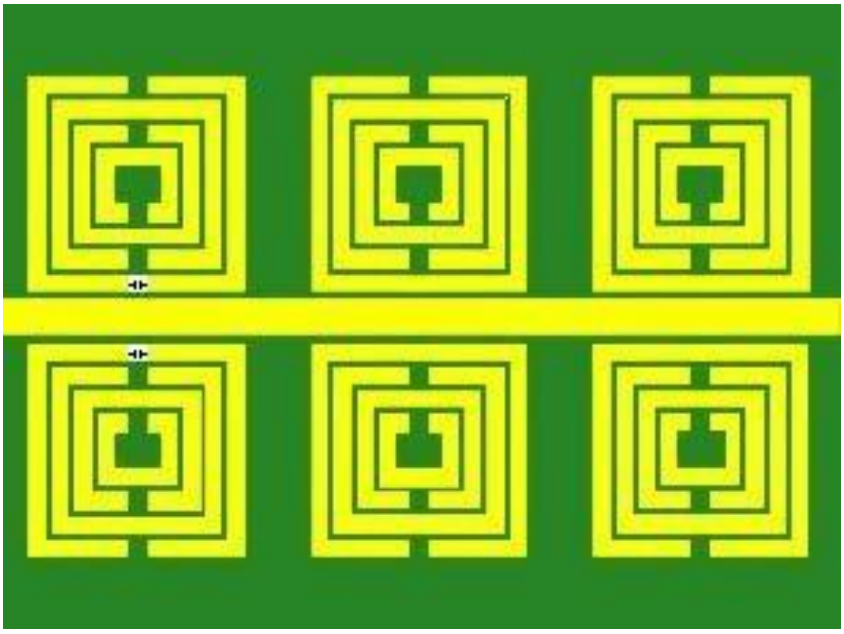

Figure 4.11. Six-element meta-material loaded Band-Notch Filter with a finite ground plane with capacitor

4.8 PERFORMANCE COMPARISON OF PROPOSED FILTER

The performance comparison between different bandstop filter configuration highlights key aspects such as frequency range, bandwidth control, insertion loss, and stop band rejection. Among the listed references, various structures employee microstrip, SIW, and waveguide Technologies, each offering distinct advantages in terms of tunability and performance. The proposed six-element metamaterial loaded band notch filter operates a wide frequency range of 1-12 GHz, utilizing a finite ground plane with capacitive tuning to achieve dynamic reconfigurability. This approach insurance effective band rejection while maintaining low insertion loss, making it a competitive solution for adaptive RF applications. The are filters stand out for its compact design, high rejection capability, and tunable characteristics, making a suitable for modern wireless communication and radar systems.

Table 4.1- Comparison of the proposed filter with the existing structure

Reference	Technology	Reconfigurability	Band-Width control	Insertion loss (dB)	Frequency Range (GHz)
[12]	Microstrip, Tuning Stubs	Moderate	Fixed	1.2	1.5-6
[13]	Microstrip, PIN Diodes	High (BPF/BSF Switching)	Switchable	0.86 (BPF)	2.4
[14]	Waveguide, Reconfigurable Elements	High	Discrete	0.9	3-9
[19]	Substrate Integrated Waveguide	Moderate High	Tunable	1.5	2-6
[20]	Waveguide, Magneto-Tunable Photonic Structures	High	Discrete Tuning	Low	4-10
Proposed Filter	Microstrip, Metamaterial, Capacitor-Tuned	High (Capacitor-Tuned Notch)	Adjustable	Low	1-12

CHAPTER- 5
CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSION

This project presents a six-element metamaterial-loaded band-notch filter with a finite ground plane and tunability achieved through capacitors. Operating within the 1 GHz to 12 GHz frequency range, the filter ensures cost-effective performance while achieving precise notch-band rejection by utilizing an FR-4 substrate and copper traces. The design has been validated through both simulation in ADS and experimental measurements using a Vector Network Analyzer (VNA), confirming its efficiency in interference suppression with minimal insertion loss. This work contributes to the advancement of reconfigurable microwave components by offering sharp rejection, a stable frequency response, and adaptability, making it well-suited for applications in wireless communication, radar systems, and cognitive radio.

5.2 SCOPE OF FUTURE WORK

By investigating different capacitor topologies and using MEMS-based tuning elements for tighter control, future research can concentrate on improving the tuning mechanism. It is possible to suppress several bands that are prone to interference by using multi-notch filtering, which would increase its suitability for use in broadband communication networks. Additionally, by reducing dielectric losses and enhancing frequency stability, low-loss substrates like Rogers RT5880 can improve performance. Applying machine learning algorithms for real-time frequency optimization and filter tuning is another possible line of inquiry. This would enable AI-driven methods to dynamically adjust the filter to changing signal conditions for increased effectiveness in adaptive communication networks. Additionally, cooperation with academic and industrial researchers and experimental validation in actual wireless scenarios might propel the development of next-generation reconfigurable RF filters.

REFERENCES

[1] Q. Guo, Z. Li, J. Su, J. Song and L. Y. Yang, "Active Frequency Selective Surface With Wide Reconfigurable Passband," *IEEE Access*, vol. 7, pp. 38348-38355, 2019.

[2] S. Arain, P. Vryonides, K. Nisar, A. Quddious and S. Nikolaou, "Novel Selective Feeding Scheme Integrated With SPDT Switches for a Reconfigurable Bandpass-to-Bandstop Filter," *IEEE Access*, vol. 9, pp. 25233-25244, 2021.

[3] Y. Guo, S. Kim, H. Gao and G. -P. Li, "Compact High Q Configurable Quint-Band Electromagnetic Bandgap Filter," *IEEE Access*, vol. 6, pp. 63703- 63711, 2018.

[4] J. C. Melgarejo *et al*., "A New Family of Reconfigurable Waveguide Filters and Diplexers for High-Power Applications," *IEEE Access*, vol. 11, pp. 25102-25119, 2023.

[5] Q. -S. Shen, M. -J. Gao, L. -S. Wu and X. -L. Zhou, "Ultra-Wideband Filtering 180° Hybrid Coupler With Super Wide Upper Stopband Using Swap Phase Inverter and Electromagnetic Bandgap Structures on Double- Sided Parallel-Strip Line," *IEEE Access*, vol. 6, pp. 41099-41106, 2018.

[6] H. Xu, Y. Wang, F. A. Ghaffar and L. Roy, "Reconfigurable Microwave Filters Implemented Using Field Programmable Microwave Substrate,"*IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 2, pp. 1344-1354, Feb. 2021.

[7] D. Psychogiou, R. Gómez-García and D. Peroulis, "RF Wide-Band Bandpass Filter With Dynamic In-Band Multi-Interference Suppression Capability," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 65, no. 7,pp. 898-902, July 2018.

[8] Rajput and B. Mukherjee, "An Electronically Reconfigurable Single to Dual-Band Bandstop Filter for RFID and Modern Wireless Communication Application," *IEEE Journal of Radio Frequency Identification*, vol. 6, pp. 534-539, 2022.

[9] L. Rodrigues, T. Varum and J. N. Matos, "The Application of Reconfigurable Filtennas in Mobile Satellite Terminals," *IEEE Access*, vol. 8, pp. 77179- 77187, 2020.

[10] W. -C. Weng, "Design and Optimization of Compact Microstrip Wideband Bandpass Filter Using Taguchi's Method," *IEEE Access*, vol. 10, pp. 107242-107249, 2022.

[11] Basit, M. I. Khattak, A. R. Sebak, A. B. Qazi and A. A. Telba, "Design of a Compact Microstrip Triple Independently Controlled Pass Bands Filter for GSM, GPS and WiFi Applications," *IEEE Access*, vol. 8, pp. 77156- 77163, 2020.

[12] M. Faisal, S. Khalid, M. U. Rehman and M. A. Rehman, "Synthesis and Design of Highly Selective Multi-Mode Dual-Band Bandstop Filter," *IEEE Access*, vol. 9, pp. 43316-43323, 2021.

[13] S. -H. Chien and Y. -S. Lin, "Novel Wideband Absorptive Bandstop Filters With Good Selectivity," *IEEE Access*, vol. 5, pp. 18847- 18861, 2017.

[14] H. Islam, S. Das, T. Bose and T. Ali, "Diode Based Reconfigurable Microwave Filters for Cognitive Radio Applications: A Review," *IEEE Access,* vol. 8, pp. 185429-185444, 2020.

[15] Z. Lu, J. Li, Y. Wu, H. Chen, S. Yang and M. Chen, "Reconfigurable RF Filter Based on Cascaded Microring Resonators," *IEEE Photonics Journal*, vol. 15, no. 3, pp. 1-6, June 2023.

[16] K. Gorur and D. Psychogiou, "Single-/Dual-Band Bandpass-to- Bandstop Filters With Center Frequency Tunability," IEEE Access, vol. 12, pp. 90697- 90706, 2024.

[17] Y. F. Tang, K. Wu and N. Khaddaj Mallat, "Development of Substrate-Integrated Waveguide Filters for Low-Cost High-Density RF and Microwave Circuit Integration: Direct-Coupled Cavity Bandpass Filters With Chebyshev Response," *IEEE Access*, vol. 3, pp. 1313-1325, 2015.

[18] K. -R. Xiang and F. -C. Chen, "Compact Microstrip Bandpass Filter With Multispurious Suppression Using Quarter-Wavelength and Half- Wavelength Uniform Impedance Resonators," *IEEE Access*, vol. 6, pp. 20364-20370, 2018.

[19] W. Yuan, X. Liu, H. Lu, W. Wu and N. Yuan, "Flexible Design Method for Microstrip Bandstop, Highpass, and Bandpass Filters Using Similar Defected Ground Structures," *IEEE Access*, vol. 7, pp. 98453-98461, 2019.

[20] R. Gómez-García, J. Rosario-De Jesus and D. Psychogiou, "Multi- Band Bandpass and Bandstop RF Filtering Couplers With Dynamically- Controlled Bands," *IEEE Access*, vol. 6, pp. 32321- 32327, 2018.

[21] M. Kheir, T. Kröger and M. Höft, "A New Class of Highly- Miniaturized Reconfigurable UWB Filters for Multi-Band Multi- Standard Transceiver Architectures," *IEEE Access*, vol. 5, pp. 1714-1723, 2017.

[22] M. R. A. Nasser, R. K. Jaiswal and D. Psychogiou, "A Compact Bandpass Filter Manifold With Ultrawide Frequency and Bandwidth Tuning," *IEEE Access*, vol. 11, pp. 41054-41060, 2023.

[23] W. Yang, M. Abu Khater, E. J. Naglich, D. Psychogiou and D. Peroulis, "Frequency-Selective Limiters Using Triple-Mode Filters," *IEEE Access*, vol. 8, pp. 114854-114863, 2020.

[24] S. Li, S. Li, J. Yuan, J. Liu and M. Shi, "Fully Tunable Bandpass Filter With Wide Bandwidth Tuning Range and Switchable Single/Dual Band," *IEEE Access*, vol. 12, pp. 36577-36585, 2024.

[25] M. D. Sinanis, P. Adhikari, T. R. Jones, M. Abdelfattah and D. Peroulis, "High-Q High Power Tunable Filters Manufactured With Injection Molding Technology," IEEE Access, vol. 10, pp. 19643- 19653, 2022.

[26] P. Vryonides, S. Arain, A. Quddious, D. Psychogiou and S. Nikolaou, "A New Class of High-Selectivity Bandpass Filters With Constant Bandwidth and 5:1 Bandwidth Tuning Ratio," *IEEE Access*, vol. 12, pp. 16489- 16497, 2024.

[27] S. I. Yahya *et al.*, "Design and Optimization of a Compact Microstrip Filtering Coupler With Low Losses and Improved Group Delay for High- Performance RF Communication Systems," *IEEE Access*, vol. 11, pp. 103976-103985, 2023.

[28] Z. Zeng, S. J. Chen and C. Fumeaux, "A Reconfigurable Filter Using Defected Ground Structure for Wideband Common-Mode Suppression," *IEEE Access*, vol. 7, pp. 36980-36990, 2019.

[29] M. Qin *et al.*, "Varactor-Based Continuously Tunable Microstrip Bandpass Filters: A Review, Issues and Future Trends," *IEEE Access*, vol. 12, pp. 57443-57457, 2024.

[30] L. Johnson *et al.*, "Novel High-Q Partially Air-Filled Pedestal Resonator and Filter Integrated in a Printed Circuit Board (PCB)," *IEEE Access*, vol. 10, pp. 101160-101167, 2022.