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Design and Analysis of a Reconfigurable Multiband Antenna for Next-Generation Wireless Communication System

Graduate School of Chosun University

Department of Information and Communication Engineering

Geun-Ok Lee

Design and Analysis of a Reconfigurable Multiband Antenna for Next-Generation Wireless Communication System

차세대 무선통신 시스템을 위한
재구성 가능한 다중대역 안테나의 설계 및 분석

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Graduate School of Chosun University
Department of Information and Communication Engineering
Geun-Ok Lee

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Advisor: Prof. Dong-You Choi

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Graduate School of Chosun University

Department of Information and Communication Engineering

Geun-Ok Lee

This is to certify that the Master's thesis of

Geun-Ok Lee

has been approved by the examining committee for the thesis requirement for the Master's degree in engineering.

Committee Chairperson	Jae-Young Pyun	(Sign)
Committee Member	Sun-Kuk Noh	(Sign)
Committee Member	Dong-You Choi	(Sign)

December 2023

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ABSTRACT

Design and Analysis of a Reconfigurable Multiband Antenna for Next-Generation Wireless Communication System

Geun-Ok Lee
Advisor: Prof. Dong-You Choi, Ph.D.
Depart. of Info. and Comm. Engg.,
Graduate School of Chosun University

A miniaturized and low-profile planar antenna is a crucial part of any wireless communication system. To cover additional narrowband services and reduce system complexity, antennas in portable devices should offer several operating bands. In this thesis, I proposed a coplanar waveguide-fed (CPW-Fed), flexible, and compact slotted patch frequency reconfigurable antenna with a compact size of (20 × 24 ㎟). The designed antenna employs a low-cost Rogers 5880 substrate with a thickness of 0.127 ㎜. This choice of substrate ensures costeffectiveness while preserving the desired performance of the antenna. The antenna radiates through five distinct frequency bands, including 5.58 ~ 6.25 ㎓, 6.05 ~ 8.81 ㎓, 8.79 ~ 9.7 ㎓, 9.7 ~ 10.22 ㎓, and 10.48 ~ 15 ㎓, depending on the switch on/off condition, thereby enabling the antenna to span a broader range of frequencies for WLAN, C-UWB, sub-6 ㎓, and X-band communications. The designed antenna is fabricated and tested in both on and off states. The measured results closely match the simulated outcomes.

국문요약

차세대 무선통신 시스템을 위한 재구성 가능한 다중대역 안테나의 설계 및 분석

이근옥

지도교수: 최동유

조선대학교 대학원 정보통신공학과

소형의 로우 프로파일 평면 안테나는 많은 무선통신 시스템에서 매우 중요한 부분이다. 휴대용 장치의 안테나는 추가적인 협대역 서비스를 커버하고 시스템 복잡성을 줄이기 위해 여러 동작 주파수 대역을 제공해야 한다.

본 논문에서는 주파수 재구성이 가능하고 유연한 20 × 24 ㎟의 소형 CPW-Fed (coplanar waveguide-fed) 안테나를 제안하였다. 제안한 안테나는 비교적 저렴하면서도 원하는 안테나 성능을 유지할 수 있도록 0.127 ㎜의 두께를 갖는 Rogers 5880 기판을 사용하였다.

제안한 안테나는 스위치 온・오프 조건에 따라 5.58 ~ 6.25 ㎓, 6.05 ~ 8.81 ㎓, 8.79 ~ 9.7 ㎓, 9.7 ~ 10.22 ㎓, 10.48 ~ 15 ㎓ 등 5개의 서로 다른 주파수 대역을 통해 방사하므로 WLAN, C-UWB, 서브-6 ㎓ 및 X-밴드 통신을 위한 여러 주파수 대역을 포괄할 수 있다.

본 논문에서 설계 및 제작한 안테나는 온・오프 조건에서 시뮬레이션과 실제 측정을 시행하였으며, 측정된 결과는 시뮬레이션 결과와 일치하고 있음을 확인하였다.

I. INTRODUCTION

The modern communication equipment comprised of many more wireless applications on a single communicating device has increased the requirement of antennas having multiband and wideband characteristics. Each application in the device requires a specific frequency to operate, i.e. Wi-Fi (2.4 ㎓), GSM (1.8 ㎓), and UMTS (2.1 ㎓). Multi-band antenna operates at certain frequency bands and is tuned to all frequencies contained by the antenna whether needed or not. The multitude of different standards in advanced communication devices like mobile phones and handheld devices requires multi-band antennas with reconfigurability characteristics. Reconfigurability in the antenna system provides diversity to system devices by altering their polarization, radiating pattern, and operating frequencies. The reconfigurable antenna is categorized into the following three types, each of which has its own applications.

- Frequency reconfigurable
- Polarization reconfigurable
- Pattern reconfigurable

The reconfigurable antenna has the tendency to operate on different frequencies with different patterns and polarizations which is the demand of modern communication systems. Reconfigurability is an essential feature of today's RF system for wireless communications. Due to its diversity, researchers have focused all their attention on the reconfigurability of antennas. Reconfigurability can be attained by connecting (providing the path for the current) or disconnecting (blocking the path of the current flow) various parts of the radiating elements using different switching techniques. A number of mechanisms allow the adaptively of circuit elements including photo conductive, varactor, PIN diodes, lumped elements, and MEMS (micro-electro-mechanical systems),

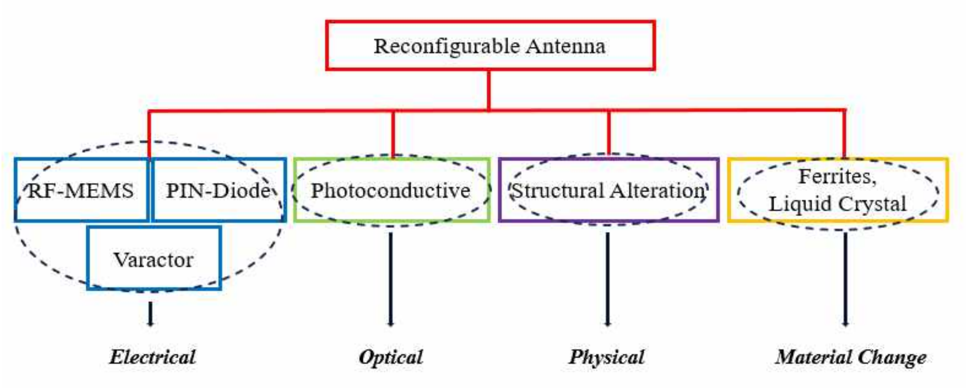


Fig. 1. Various mechanisms for Reconfigurability

and can also be achieved by changing material shown in fig. 1 [1]. Lumped elements are usually used because of their easy integration in the radiating structure. Other switching techniques are complex and expensive have low reliability and needed high bias voltage in comparison with the lumped switching elements.

A. Problem Statement

An antenna that operates across multiple frequency bands has garnered significant attention due to the widespread use of modern wireless technology and the growing demand from consumers for multiple services within a single device.

Traditionally, each frequency band corresponds to a specific wireless service, necessitating a multi-band antenna to accommodate various services within one wireless device. These multi-band antennas can effectively function across different frequency bands, maintaining favorable signal strength and consistent radiation patterns.

In any scenario, multi-band antennas emit electromagnetic waves concurrently across all supported frequencies, including the intended frequency for communication. It's worth noting that prolonged exposure to electromagnetic radiation can have negative implications for human health.

To address the challenges posed by multi-band antennas, reconfigurable antennas have emerged as a solution. These antennas can be adjusted to operate within desired frequency bands, radiation patterns, and polarizations. In today's context, flexible antennas have gained prominence due to their slim profile, lightweight nature, and durability. Although various flexible substrates have been explored, many lack reconfigurability. Consequently, a proposal has been put forth for a compact, cost-effective, flexible, and reconfigurable antenna. This design incorporates both flexibility and reconfigurability, making it highly appealing for applications that require adaptability and versatility, including conformal designs and various other use cases.

B. Thesis Objective

The main aim and objective of this project is to design a compact CPW-fed flexible and frequency reconfigurable antenna. Therefore a novel design is proposed which has gone through the simulation process several times until the final design is achieved. The main contributions are enumerated as:

- To propose a novel, compact, and flexible design. That can be used for multiple applications
- To obtain a useful frequency band for both ON/OFF conditions
- To enhance the gain and bandwidth using a flexible substrate

C. Research Scope and Methodology

In this thesis, a compact and low-profile frequency reconfigurable conventional antenna is designed. The flexible material is used as a substrate. The CPW feeding technique is the use of reduced thickness and complexity of the design. To make the antenna reconfigurable a 1 mm slot is reserved in the radiating part. The reconfigurable conventional antenna is then fabricated and measured. The antenna performance under different bend and plan conditions is examined.

To achieve our objective, different activities have been outlined:

- Detailed study of Reconfigurable antennas by taking into consideration its advantages and drawbacks
- Slotted shape antenna design
- Introducing a switch in the right position to make the antenna reconfigurable
- Analysis of the proposed design
- Fabrication and testing of the proposed design to validate the performances

D. Organization of Thesis

This thesis consists of four chapters. An overview of each chapter is given below chapter 1 gives a brief introduction, problems, objectives, and scope of the project. chapter 2 gives a brief Literature review of the proposed work, different challenges are discussed in this chapter. Similarly, chapter 3 discusses the designing, analysis, and measured results of the proposed compact and slotted-shaped antenna in terms of return loss, gain pattern, voltage standing waveratio, and efficiency. while chapter 4 concludes the proposed work and gives some future recommendations.

II. Theory and background

A. Reconfigurable Antennas

Modern telecommunication extensively focuses on developing the internet and mobile devices such devices are able to operate on more than one application. Each application has its own operating frequency range, i.e. Wi-Fi (Wireless fidelity), bluetooth, GPS (Global positioning system), GSM (Global system for mobile communication), and Wi-MAX. Being the most critical part of communication, the system antenna must be designed and deployed efficiently. So that it can utilize the available spectrum effectively. In this perspective, there are three antenna methodologies, simple antenna, and antenna operating at multiband and reconfigurable antennas. Applications of these three types of antennas have their own merits and demerits. Better performance can be achieved by implanting multiple single-band antennas in a device for different applications, but at the cost of size, complexity as well coupling due to little space in between. To support multiple services multiband antenna is the best candidate that transmits and receives EM waves at multiple frequencies with optimum gain, directivity, and radiation efficiency. Currently, some approaches for the design of multiband antennas like the integration of a metamaterial-inspired split ring resonator [2] and insertion of slots [3] within the radiating elements have been proposed. Defective ground planes [4] are also proposed to get multiple frequency bands. However, they transmit all resonances irrespective of the end user requirement [5]. In other words, multiband antennas cannot be tuned to the desired frequency. Moreover, in multiband antennas, the chance of jamming and unavailability of wireless services increases due to poor isolation between different operating frequency bands [6], [7]. To overcome these limitations researchers have developed a possible solution, i.e. reconfigurable antennas. Reconfigurable antennas have great potential to mitigate the problems encountered in single-band antennas and multiband antennas. There are various reconfigurable antennas such as polarization reconfigurable [8], frequency reconfigurable [9], and pattern reconfigurable [10].

1. Frequency Reconfigurable

These types of reconfigurable antennas have the tendency to operate on more than one frequency spectrum, which depends on the switching condition of an antenna (on-off states). Frequency reconfigurability can obtain by incorporating switches of different types in radiating element of an antenna. Only a single element is required for the multifunction communication system, this will result in the size reduction of the communication devices. Thus reconfigurable antennas eliminate the requirement for multiband and wide-band antennas. Reconfigurability is actually changing the current distribution within the radiating element and that can be realized by employing various switching techniques such as PIN Diode [11], Varactor diode [12], Radiofrequency micro-electro-mechanical system (RFMEMS) switches [13], [14], variable capacitance switches [15], and lumped element [16]. A variety of reconfigurable antennas with different switching techniques has been demonstrated. A tri-band 35 × 53 ㎟ (2.45 ㎓, 3.50 ㎓, and 5.20 ㎓) frequency reconfigurable antenna using a lumped element is reported in [17]. A Novel 40 × 40 ㎟ antenna is presented in [18] by introducing the switchable slots in the ground plan, the antenna can be switched between a narrow band, UWB, and dual-band. An extensive antenna of 90 × 50 ㎟ is designed for Industrial, Scientific, and Medical (ISM) applications [19]. Although smallsize reconfigurable antennas have been reported in the literature. A compact tri-band frequency reconfigurable antenna with a size of 27 × 25 ㎟ is presented in [20]. This slot antenna uses two-pin diodes for frequency reconfiguration. The antenna proposed in [21] employs eight varactor diodes and covers only five band operations. This design has a complex geometry. However, the main complexity comes from a large number of switches and associated biasing networks. The number of switches will increase insertion loss, complicate the circuitry and degrade the overall performance of the system. However, most of the aforesaid designs are implemented on a rigid substrate and few designs have a flexible substrate but flexibility analyses are not reported. Antennas having rigid substrates are not suitable for conformal applications.

2. Pattern Reconfigurable Antennas

On the other hand, the ability of the antennas to change their radiation characteristics is termed as pattern reconfigurable antennas. The radiation pattern reconfigurable antenna has the ability to keep off noise sources or deliberate jamming signals and preserve energy by pointing the antenna pattern to specific users. Various antenna structures and techniques are applied by the researchers to achieve the pattern reconfigurability of an antenna. In [22] a basic antenna structure consisting of an L-shaped slot, PIN diodes, and lumped capacitors is designed. By carefully controlling the diodes, current distribution around the slot can be varied, resulting in different radiation patterns thus pattern reconfigurable antenna is obtained. The designed structure can be extended to achieve frequency and pattern reconfigurability by introducing varactor diodes. In [23] the author designs a square ring patch antenna with pattern reconfigurable features using PIN diodes. The PIN diode acts as a short when it is forward biased and when reversed biased it acts as open. By controlling the state of the PIN diode switches the designed antenna allows its radiation pattern to be switched between broad-side and conical radiations at the same frequency.

3. Polarization Reconfigurable Antennas

Similarly, there are a lot of applications that require antennas with polarization reconfigurable features. A polarization reconfigurable antenna is an antenna in which the polarization state can be changed dynamically either by vertical, horizontal, or circular (right-hand or left-hand) polarization according to the application. Antennas with polarization diversity are called polarization reconfigurable antennas. Three types of polarization are linear, circular, and elliptical polarizations. Polarization reconfigurability methods are used to keep the quality of the communication effective by selecting the type of polarization such as linear polarization and vertical polarization. As discussed, these types of antennas can alter frequency, radiation, and polarization. The performance characteristics can be altered or modified by changing the current distribution on an antenna structure, by using diodes, mechanically movable parts, tunable materials, and attenuators. In reconfigurability, a null is placed in by the antenna in a pattern, which can switch the antenna polarization from left-hand circular polarization to right-hand circular polarization or switch the antenna operation between different frequency bands. So in this manner, two or more antennas are replaced by one single antenna for attaining multiple goals. In [24] E-shaped polarization reconfigurable antenna is designed to integrate with two PIN diode switches. The designed antenna structure is capable of altering its polarization from left-hand circular to right-hand circular polarization depending on the states of the RF switches. The idea of attaining reconfigurability is comparatively old. At the start of the 1930s, the nulls of an array having two elements steered by a finetuned variable-phase-changer to determine the path of the arrival of the signal [25].

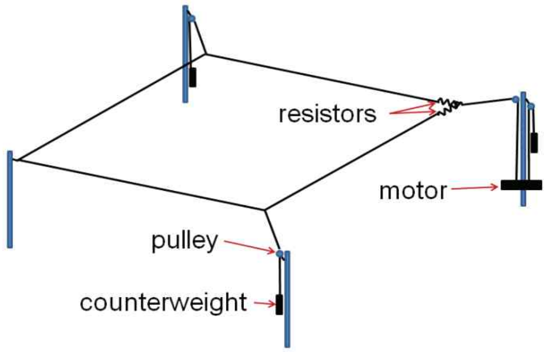


Fig. 2. Horizontal Steerable Rhombic antenna [26]

Beck and Burce alter the volume of the rhombic antenna by extending wires by means of the weights and motors as shown in fig. 2 [26]. The rhombus element lengths were 184 m, and the rhombus inner angles are between 132 degrees and 164 degrees. Reconfiguring this antenna comprised of sitting the length of greater axis above 100 m, altering the length antenna guides beam of the antenna in the elevation plane. In 1979, reconfigurability is defined as 'the ability of the antenna to steer the beam shape upon 0 control or demand of the user'. In the 1990s, the efforts of research groups in England described their work for controlling the radiation of the parabolic dish by altering the aperture of the parabolic dish reflector [26]. From the mid of 1990s till the present, reconfigurability projects mainly involve microstrip patch antennas, and several methods of reconfigurability are applied to alter the current distribution in the patch of an antenna in order to change the performance characteristics of the antenna according to the user demand.

B. Principles of Reconfigurability

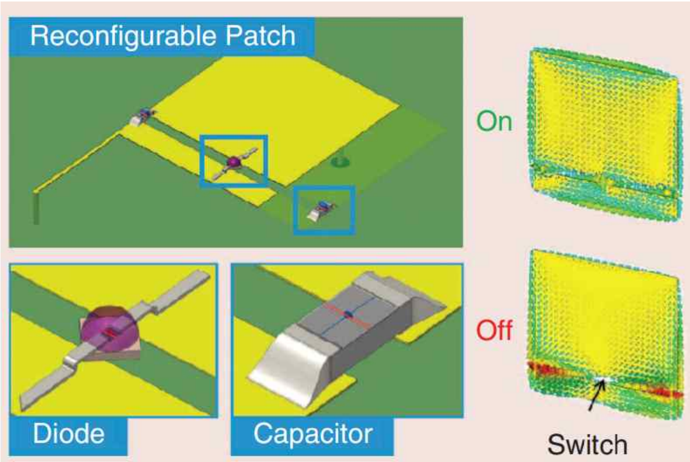


Fig. 3. Reconfigurable patch antenna having slot in the patch.
The right side of the figure shows the current distribution [27]

The current flow on the antenna structure determines the antenna radiation characteristics. Altering or changing the current on an antenna structure will result in the reconfigurability of an antenna. These changes in the current flow can be attained by slightly modified in the geometry of antennas or their material characteristics. A patch antenna having a slot is shown in fig. 3 [27]. A part of the patch is branched from the remainder of the patch by using a slot in the radiating element. The slot is bridged centrally by using Schottky diodes and two blocking capacitors are used at the ends of the slot. A pin feed is used for the excitation of an antenna so that the radiation of the patch is circularly polarized. The state of the diode depends on the excitation of the larger part of the patch by applying voltage, i.e. forward bias or reverse bias. The smaller part of the patch is grounded in order to get high impedance at resonance at the patch edge. By altering the state of the switch used in the slot, I can change or alter the current path on the radiating patch of an antenna as shown on the right side of fig. 3. Thus altering the electric field will cause the antenna to switch from left-hand circular polarization to right-hand circular polarization (as shown on the right of fig. 3).

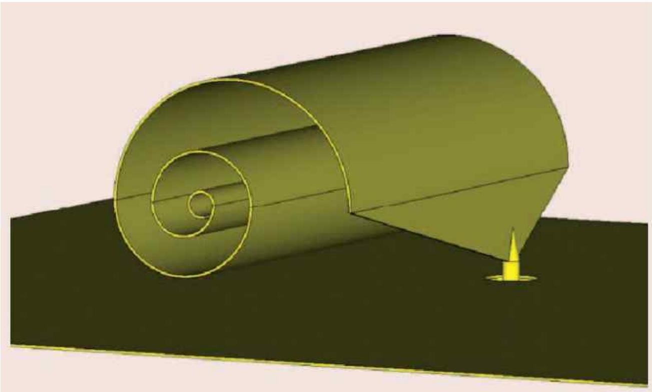


Fig. 4. Rollable UWB reconfigurable antenna [27]

This switching technique differentiates the switchable reconfigurable antennas from the phased element array antennas. In phase array antennas the only change is in the beam of each array element, while there is no change in the antenna central performance characteristics. The Antenna can be reconfigured by using several ways and different parameters and characteristics of an antenna can be reconfigured. So the first thing that comes in front is the differentiation between the discrete and the continuous reconfigurable antennas. The patch antenna is shown in fig. 3 is a discrete reconfigurable antenna, which can switch between two operating modes depending on the state of the Schottky diodes i.e. forward bias or reverse bias. On the other hand, the characteristics of the rollable UWB antennas alter continuously depending on the fact that how tightly wound the antenna is, as shown in fig. 4 [27].

All the properties of an antenna such as operating frequency, far field, radiation pattern, and polarization are reconfigured, but it is not an easy task to reconfigure them independently, because changing one characteristic has an effect on the other characteristic of an antenna. So a deliberate design and parameter analysis will be required.

1. Reconfigurability through Mechanical changes

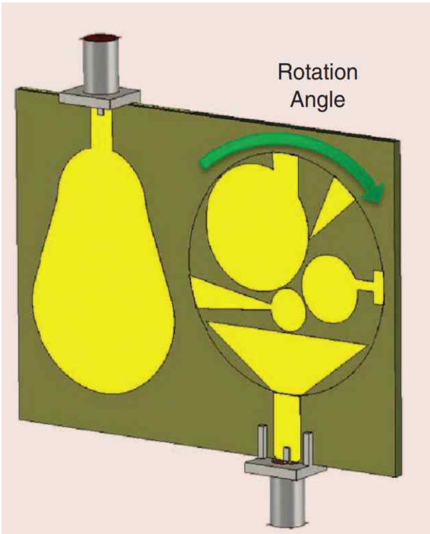


Fig. 5. Reconfigurability by mechanical means [27]

The simulation of mechanical changes in the structure of an antenna is comparatively simple. The desired geometry is obtained by changing one or more parameters mechanically. Two of the examples are discussed below here. The fig. 5, the antenna is comprised of two main parts, the UWB sensing antenna is on the left of the design, and the antenna on the right side is a transmitting antenna that can be reconfigurable by mechanical means by rotating a disc at a particular rotating angle which makes contact with the feed and becomes active [27]. And the second example is discussed in fig. 4 that the rollable UWB antennas can change their characteristics continuously which depends on how tight (more or less) the antenna is wound using a motor around the spindle.

2. Reconfigurability by changing the properties of the material

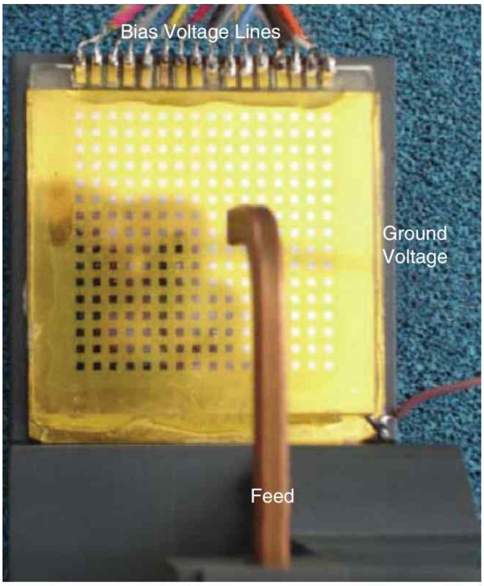


Fig. 6. Patch array using liquid crystal substrates,
with bias voltages on the top of the array [27]

Changing Material properties means the use of materials that can alter their properties under the driving of an external electric field. This is a simple and attractive technology used to reconfigure the antenna's characteristics. Various materials are used, one of them is a liquid crystal. Applying a static electric field to the liquid crystal changes its permittivity. Fig. 6 [27] shows the patch array having liquid crystal used as material substrate. The antenna is a reflector array of patch elements, which is exited or fed from the top end of the use of the openended waveguides [27].

Each column of the patch elements is excited by the use of the bias voltage paths as shown in fig. 6. So thus each column has therefore a substrate that has a slightly different value of the permittivity and a slightly different phase of reflection as compared to the other columns. So in this way, the beam reflected from the patch array can be guided by the adjustment of the bias voltages.

3. Reconfiguration with Switches

In the modern era switches are the most commonly used reconfiguration tool. The switch provides different routes for the current flow onto the structure of an antenna and also isolates different elements of the antenna from the antenna structure. There are different types of the switches that are used for achieving the reconfigurability of an antenna, such as PIN diode, RF switches, lumped elements, microelectromechanical systems (MEMS), and field effect transistors (FETS). Various types of switches have various advantages and disadvantages according to their bandwidth, insertion loss, bias current, speed of switching, and actuation voltage.

The simulation of the switches depends on the different degrees of complication. It also depends on the availability of the resources and on the expected accuracy. At the initial level, the switches can be made of the metal tab, these are the switches used between ON and OFF state.

But at the extra or additional degree of complication, the switches require a type of simulation called the hybrid electro-magnet-circuit simulation [27]. Different simulation software is used for this type of requirement, but the most commonly used and effective simulation tool is Computer simulation technology, CST Microwave Studio.

III. Proposed Multiband Frequency Reconfigurable Antenna

A. Antenna Configuration

A multiband slotted patch-shaped reconfigurable antenna is illustrated in fig. 7. The compactness and multi-resonance of the designed antenna are achieved by introducing slots on the patch. To obtain a low profile and wide bandwidth, a single feed CPW has a width of 'Wt' and two gaps of 'g' are used. This approach reduced the fabrication complexity because the radiator and ground were placed on the common side of the dielectric substrate.

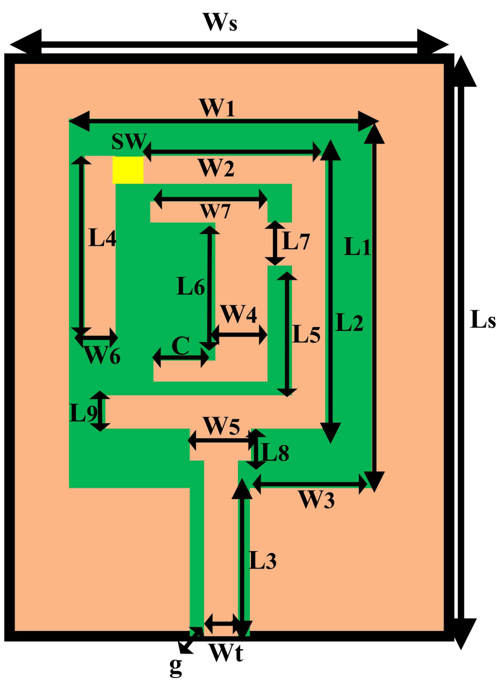


Fig. 7. Front view of the proposed slotted patched multiband frequency reconfigurable antenna

Table 1. Attributes of the proposed design

Parameter	Size (㎜)	Parameter	Size (㎜)	Parameter	Size (㎜)
Ls	24	L7	2	W4	2
L1	15.8	L8	1.2	W5	2.4
L2	12	L9	1	W6	1
L3	7.3	Ws	20	W7	5
L4	8	W1	13	Wt	1.52
L5	6.5	W2	7.8	g	0.55
L6	7	W3	4.84	C	3

The substrate material utilized is Rogers 5880, which has a thickness of 0.127 ㎜ and possesses a loss tangent of 0.0009 and a permittivity of 2.2. To achieve the targeted impedance matching of 50 Ω, the gaps (g) between the feedline and ground planes, the width of the feedline (Wt), and other dimensions are essential. The antenna has dimensions of 20 × 24 × 0.127 ㎣ and operates in five frequency bands. Table 1 lists the optimized dimensions of the designed reconfigurable antenna.

To optimize matching, the feedline impedance can be computed as [28]

$$Z_O = \frac{30\pi}{\sqrt{\varepsilon_e}} \frac{K(k_o^{'})}{K(k_o)} \tag{1}$$

where ε_e represents the effective permittivity of the substrate. $K(k_o), K(k_o^{'}), K(k_1),$ and $K(k_1^{'})$ are the modulus values of the complete integral, which can be evaluated as given below.

$$\varepsilon_e = 1 + \left(\frac{\varepsilon_r - 1}{2}\right)\left(\frac{K(k_1)K(k_o')}{K(k_1')K(k_o)}\right) \tag{2}$$

$$k_o = \frac{S}{S+2d} \tag{3}$$

$$k_o' = \sqrt{1-k_o^2} \tag{4}$$

$$k_1 = \frac{\sinh(\pi S/4h)}{\sinh\pi(S+2d)/4h} \tag{5}$$

$$k_1' = \sqrt{1-k_1^2} \tag{6}$$

Similarly, for a specific resonance, the effective antenna length is determined using transmission line theory [29].

$$L_r = \frac{c}{4f_r\sqrt{\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}(1+12\frac{h}{w})-0.5}} \tag{7}$$

In the aforementioned equation, ε_r and h represent the relative dielectric constant and thickness of the substrate, respectively.

B. Design Methodology

Fig. 8 and 9 present the step-by-step procedure for obtaining the desired CPW-fed slotted patch multiband frequency reconfigurable antenna with its corresponding S_{11}, which indicates the degree of impedance matching achieved between the antenna and the connected transmission line. A perfect match has a reflection coefficient of zero (linear scale), whereas a mismatch has a reflection coefficient with some nonzero values. As observed in the simulations, the corresponding S_{11} is less than -10 dB in all the operating bands. An investigation of the antenna through a parametric study is conducted based on S_{11}. Initially, a single C-shaped resonator is designed along with a CPW feedline and resonates at 11.5 GHz. By adding another strip, the frequency shifts to 7.9 GHz. A central patch is then added in between the C-shaped resonator, which is operating at two wide bands, namely, 6.12 ~ 8.72 GHz and 11.4 ~ 15 GHz. All these variations and their corresponding S-parameters are shown in fig. 3. The final intended design was obtained by introducing lumped elements at a precise location. A 1 mm slot was allocated for the switch in the upper part of the radiator. This resulted in resonance in the five frequency bands. Fig. 10 presents a flowchart outlining the various steps required to obtain the desired results.

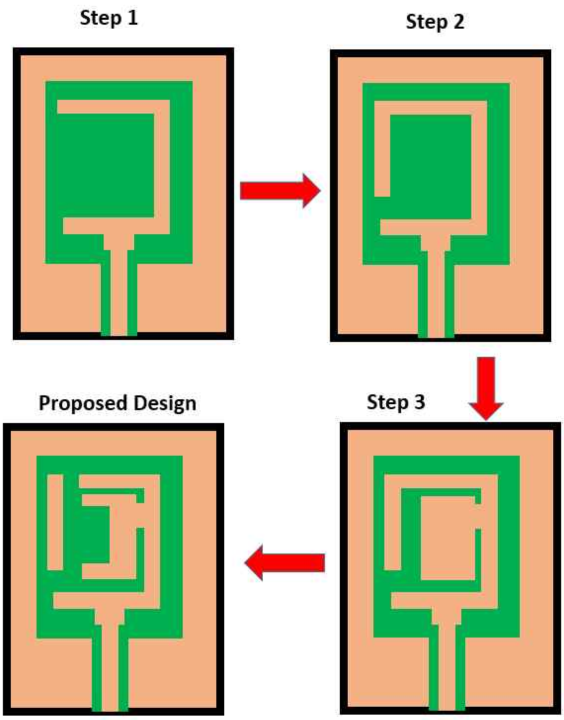


Fig. 8. Steps of the proposed antenna

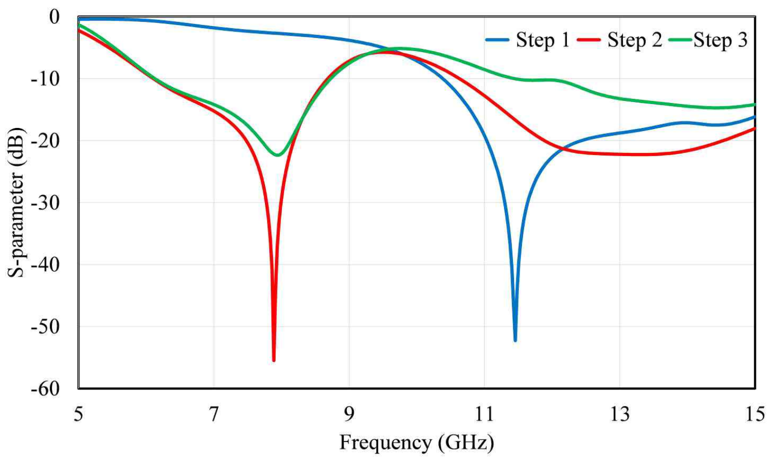


Fig. 9. Reflection coefficients for Steps 1, 2, 3

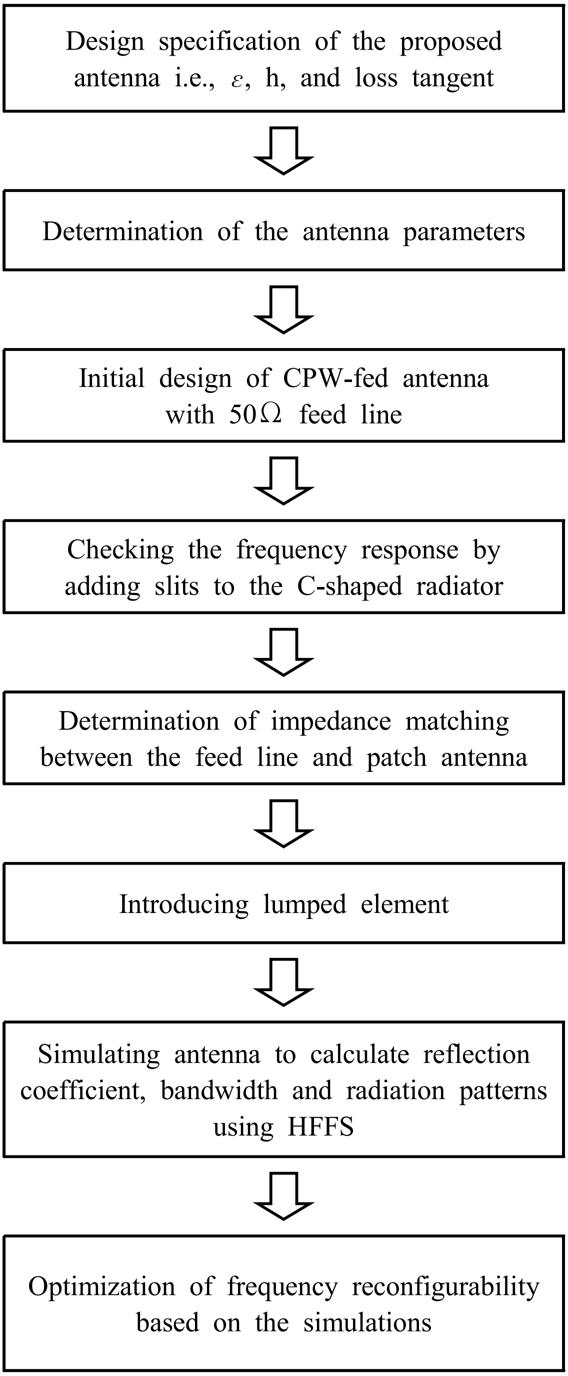


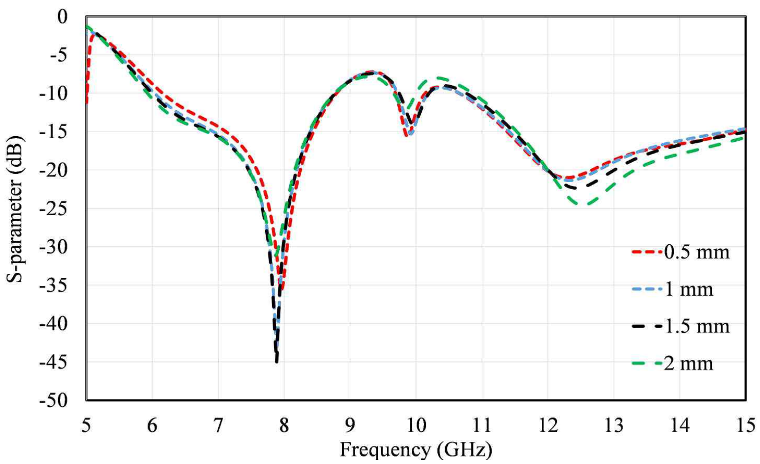
Fig. 10. Flow chart of the antenna design methodology

C. Parametric Analysis

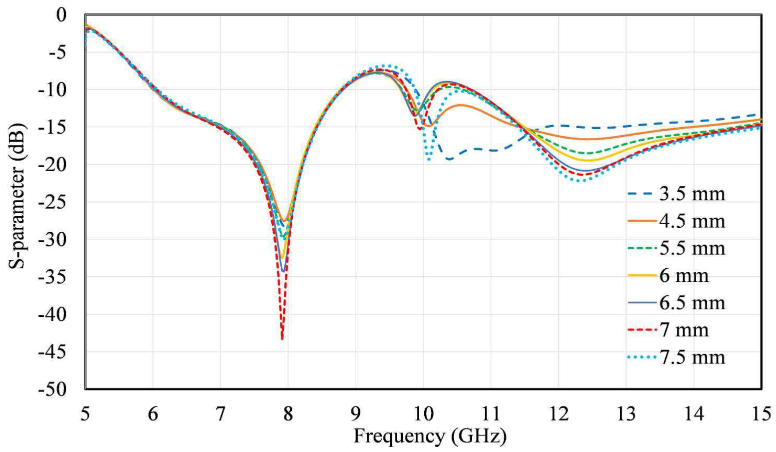
The parametric analysis of various parameters of the proposed antenna is performed to assess the impact of different parameters on the antenna performance. The presented antenna is analyzed using the parameter W6, L6, and C. It can be observed from fig. 11(a), by varying the parameter W6, changing the higher frequency. The higher band is changing 12.1 ~ 12.7 ㎓.

However, the effect on the center frequency is negligible. Thus it is concluded that the higher frequency can be controlled by the parameter W6. Similarly, by varying the parameter L6, the reflection amplitude of the higher frequency varies while it has a negligible effect on the first bands, however, a small variation is observed at the center resonance. Fig. 11(b) presents the simulated S_{11} versus frequencies for different values of L6.

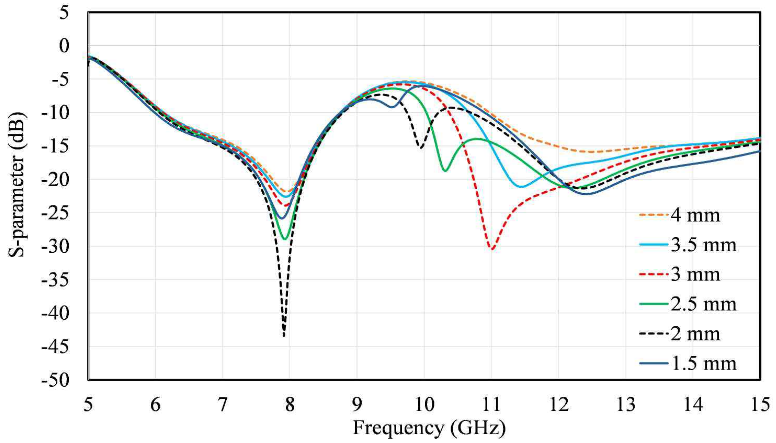
Fig. 11(c) presents the S-parameter versus frequencies plot for varying the parameter C, It is demonstrated that the parameter C is effective in shifting the center bands. By increasing the value of C from 1.5 ~ 4 ㎜, the center band is shifting toward the higher frequency, Thus it is concluded from the parametric analysis that the center band can be controlled by varying the parameter C.



(a) W6



(b) L6



(c) C

Fig. 11. Reflection coefficient against frequencies for different parameters in (a) W6, (b) L6, (c) C

D. Results and Discussion

The proposed slotted-shaped frequency reconfigurable antenna was designed and analyzed using HFSS simulation software. A prototype was fabricated for both scenarios (ON and OFF) to test the antenna's performance. Fig. 12 illustrates the prototype of the fabricated design and the measurement setup used to capture the scattering parameters. The S-parameters of the design were measured using a network analyzer model N5227B, which operated within the frequency range of 10 ㎒ to 67 ㎓.

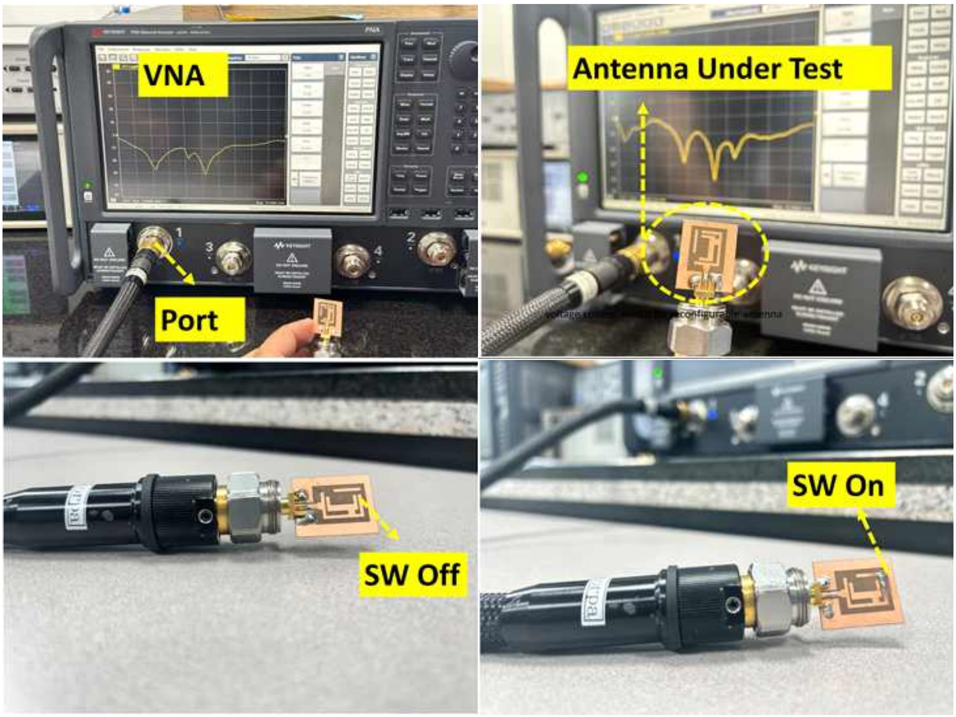


Fig. 12. Fabricated Design and Measurement setup for S-parameters

1. Switch ON

Fig. 13 shows the simulated and measured S-parameters for the switch-on condition. When the switch was turned ON, the current followed a prolonged path, resulting in full radiation. In this scenario, the antenna radiated in three distinct bands. The initial frequency band spans 6.05 ~ 9.74 ㎓, with a central frequency of 7.9 ㎓ and a bandwidth of 2,730 ㎒. This range is crucial within the X-band spectrum that is commonly used for wireless communication.

It encompasses the military requirements for satellite uplink and the mobile satellite sub-band 7.9 ~ 8 ㎓, catering to naval and land mobile satellite earth stations. For earth exploration satellite purposes, the military requirements for downlink fall within the frequency range of 8 ㎓ to 8.4 ㎓.

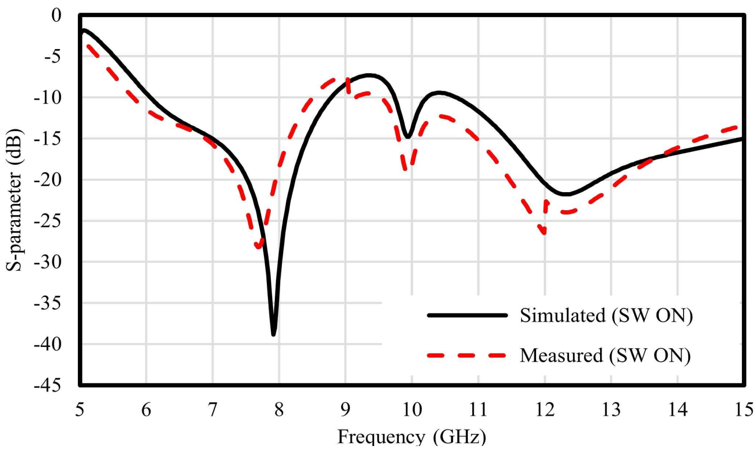


Fig. 13. Simulated and measured S_{11} characteristics of the proposed antenna (SW ON)

The second band of the antenna spans 9.74 ~ 10.22 ㎓, with a center frequency of 9.95 ㎓ and a bandwidth of 270 ㎒. This band specifically covers the X-band used for satellite communication. Finally, the third band extends 10.7 ~ 15 ㎓, with a center frequency of 12.29 ㎓ and a bandwidth exceeding 4,300 ㎒. This wideband covers various applications, such as 5G communication 12.2 ~ 12.7 ㎓, and satellite internet providers Starlink, and SpaceX use the 12 ㎓ band. The proposed design shows S_{11} of -38 dB, -14 dB, and -21.65 dB at 7.9 GHz, 9.9 GHz, and 12.29 GHz, respectively, guaranteeing perfect matching. A close agreement was observed between the measured and simulated results.

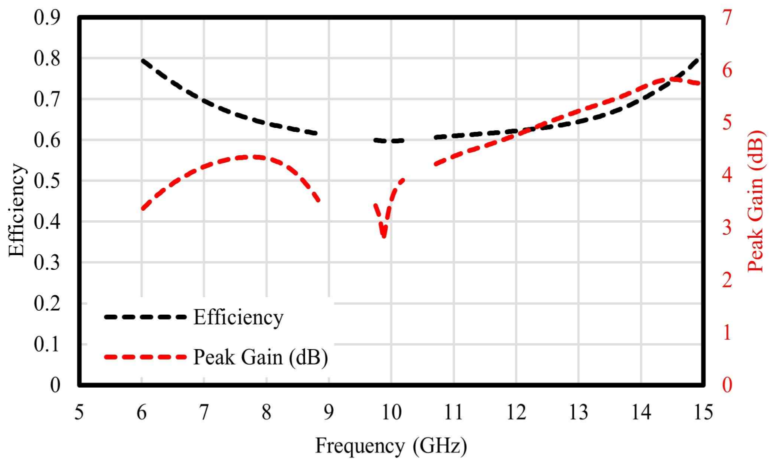
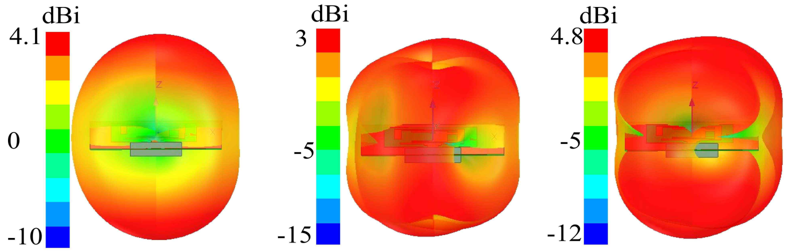


Fig. 14. Simulated efficiency and peak gain (SW ON)

Similarly, the peak gain and radiation efficiency plots for the SW-ON mode are shown in fig. 14. Efficiency values of 64 %, 59.7 %, and 62.5 % are observed for 7.9 GHz, 9.9 GHz, and 12.2 GHz, respectively. Similarly, peak gains of 4.33 dBi, 2.95 dBi, and 4.89 dBi are observed for 7.9 GHz, 9.9 GHz, and 12.2 GHz, respectively, making the proposed design an efficient candidate for various wireless applications.

The 3D radiation patterns of the proposed slotted-patch multiband frequency reconfigurable antenna for SW-ON conditions are shown here. It can be observed from fig. 15 that the presented design has a good radiation pattern along the +z and -z axes with minimum side lobes. Maximum gains of 4.1 dB, 3 dB, and 4.8 dB were observed for the three desired frequency bands of 7.9 GHz, 9.9 GHz, and 12.3 GHz, respectively. At higher frequencies, the radiation near the port is highly energized and radiates more power, which then decreases toward lower frequencies.

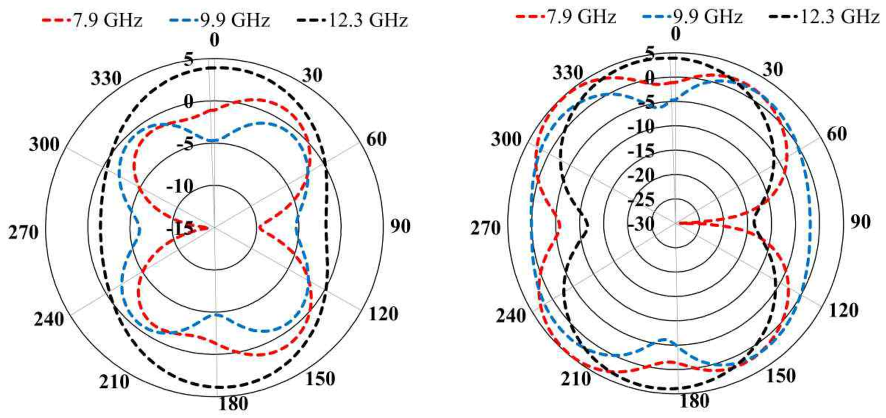


(a) 7.9 ㎓ (b) 9.9 ㎓ (c) 12.3 ㎓

Fig. 15. 3D radiation pattern (SW ON) (a) 7.9 ㎓, (b) 9.9 ㎓, (c) 12.3 ㎓

Fig. 16 illustrates the simulated 2D radiation patterns for the E and H fields of the antenna. In this instance, with the switch turned ON, the antenna resonates at three distinct frequency bands spanning 6.05 ~ 15 ㎓.

Fig. 16(a) shows the E-plane radiation pattern of the multi-band frequency reconfigurable antenna at frequencies of 7.9 ㎓, 9.9 ㎓, and 12.3 ㎓. The antenna has four lobe configuration at 9.9 ㎓, and bidirectional radiation patterns at 12.3 ㎓ and 7.9 ㎓. Fig. 16(b) illustrates the H-plane of the proposed antenna at the three resonances. The antenna design exhibits nearly identical radiation patterns across different frequency bands. This makes it a highly suitable candidate for insertion into portable electronics intended for wireless applications.



(a) E-plane (b) H-plane

Fig. 16. Simulated radiation pattern (SW ON) (a) E-plane, (b) H-plane

The summarized results for SW-ON conditions are presented in Table 2.

Table 2. Summarized results (SW ON)

Frequency (㎓)	7.9	9.9	12.3
Return loss (dB)	-38	-15	-21
Bandwidth (㎓)	2.76	0.48	5.3
Gain (dBi)	4.1	3	4.8
Efficiency (%)	64.4	59.7	62.5

2. Switch OFF

The simulated and measured S-paramters of the switch-off condition are shown in fig. 17. In this mode, the antenna operates at three different resonances. The first frequency band ranges 5.58 ~ 6.25 ㎓, with a center frequency of 5.84 ㎓ and a bandwidth of 670 ㎒. This range covers the upper portion of the WLAN band, specifically the frequencies around 5.9 ㎓ and 6 ㎓. The second frequency band spans 8.79 ~ 9.7 ㎓, with a center frequency of 9.18 ㎓ and a bandwidth of 910 ㎒. This band falls within the X-band spectrum. The third band is 10.4 ~ 15 ㎓, with a center frequency of 13.75 ㎓ and a bandwidth of more than 4,600 ㎒. This band covers various applications for 5G communications 12.2 ~ 12.7 ㎓ and satellite Internet providers Starlink and SpaceX use the 12 ㎓ bands. The proposed design shows S_{11} of -35 dB, -18 dB, and -27 dB, at 5.8 ㎓, 9.1 ㎓, and 13.75 ㎓, respectively, guaranteeing perfect matching. A close agreement is observed between the measured and simulated results.

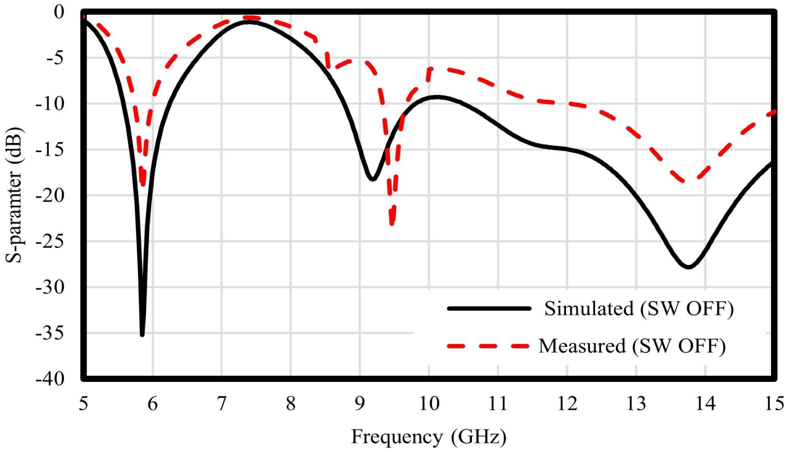


Fig. 17. Simulated and measured S_{11} characteristics of the proposed antenna (SW OFF)

The peak gain and radiation efficiency plots for the SW-OFF mode are illustrated in fig. 18. Efficiency values of 99 %, 84 %, and 86 % are observed at 5.8 ㎓, 9.2 ㎓, and 13.75 ㎓, respectively. Similarly, peak gains of 2.62 dBi, 3.27 dBi, and 3.99 dBi are observed for 5.8 ㎓, 9.2 ㎓, and 13.75 ㎓, respectively, making the proposed slotted patch reconfigurable antenna a better candidate for wireless communication.

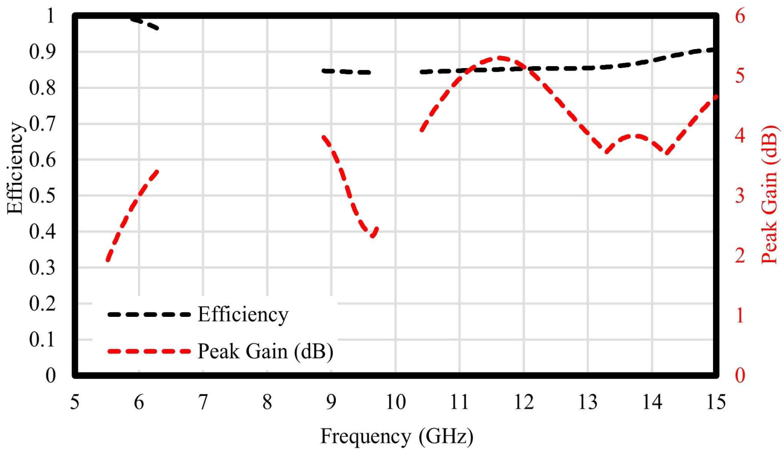
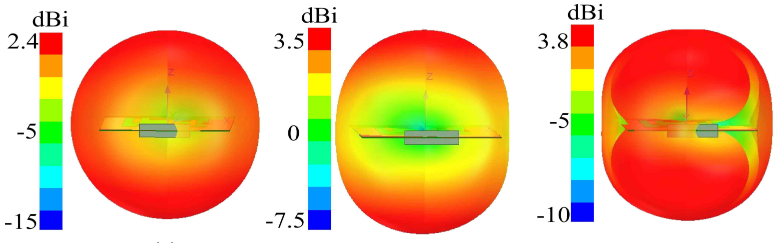


Fig. 18. Simulated efficiency and peak gain (SW OFF)



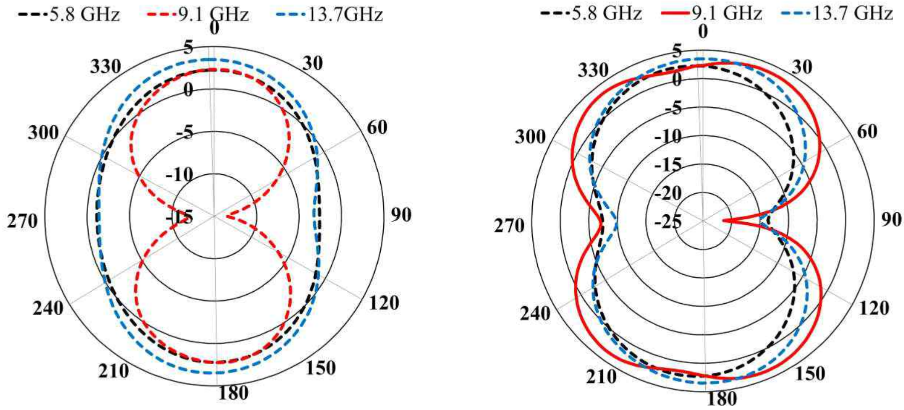
(a) 5.8 ㎓ (b) 9.1 ㎓ (c) 13.7 ㎓

Fig. 19. 3D radiation pattern (SW OFF) (a) 5.8 ㎓, (b) 9.1 ㎓, (c) 13.7 ㎓

The 3D radiation patterns of the proposed reconfigurable antenna for the SW-OFF condition are presented. It can be observed from fig. 19 that the presented design has a perfect radiation pattern along the +z and -z axes with minimum side lobes. Maximum gains of 2.4 dB, 3.5 dB, and 3.8 dB can be observed for the three desired frequency bands of 5.8 ㎓, 9.1 ㎓, and 13.7 ㎓, respectively. At higher frequencies, the radiation near the port is highly energized and radiates more power.

Similarly, Fig. 20 illustrates the simulated 2D radiation patterns for both E and H fields for the SW-OFF condition. The antenna radiates at three different frequency bands, 5.58 ~ 15 ㎓. Fig. 20(a) presents the E-plane of the proposed reconfigurable antenna at 5.8 ㎓, 9.1 ㎓, and 13.7 ㎓.

The antenna exhibits a bidirectional radiation pattern at 13.7 ㎓ and an omnidirectional radiation pattern at 9.1 ㎓ and 13.7 ㎓. Fig. 20(b) illustrates the H-plane of the proposed antenna at the three resonant frequencies. The design exhibited almost the same radiation pattern for all the desired frequencies. This makes the antenna an excellent option for incorporation into portable electronics for wireless applications.



(a) E-plane (b) H-plane

Fig. 20. Simulated radiation pattern (SW OFF) (a) E-plane, (b) H-plane

The summarized results for SW-OFF conditions are presented in Table 3.

Table 3. Summarized results (SW OFF)

Frequency (GHz)	5.85	9.18	13.75
Return loss (dB)	-35	-18	-27
Bandwidth (GHz)	0.67	0.9	5.6
Gain (dBi)	2.4	3.5	3.8
Efficiency (%)	99	84	86

E. Comparison with State of the Art Designs

To emphasize the novelty of this thesis, the designed antenna is compared with state-of-the-art designs. The comparison results are summarized in Table 4, which presents the key findings and highlights the advancements achieved by the proposed antenna.

In [30], a frequency-reconfigurable antenna was presented using a low-cost FR4 substrate, and a wide bandwidth was achieved at the cost of several switches and the antenna size. In addition, [31] presented a circular polarized rotated L-shaped antenna using defected ground structure; however, the proposed design operates on a single frequency band. Reference [32] reports the design of a triple band reconfigurable antenna for IoT applications, by utilizing two switches three different bands are achieved. The proposed design has better efficiency of more than 90 % but has a gain of ≤ 2 dBi for all three operating bands. A miniaturized 20 × 30 ㎟ antenna for sub-6 ㎓ 5G applications was proposed in [33], which can operate 3.05 ~ 3.74 ㎓ The performance is observed under two different bending conditions, later on, an eight ports MIMO antenna is designed with a common ground plane. Considering all the state-of-the-art designs presented in Table 4, it can be concluded that the proposed slotted patch multiband frequency reconfigurable antenna is a better candidate for wireless applications.

Table 4. Performance comparison with other designs

Ref.	[30]	[31]	[32]	[33]	[34]	[35]	[36]	[37]	Proposed work [38]
Dimensions (㎟)	3,900	900	4,000	600	875	900	337.5	2,852	480
Material used	FR4	FR4	FR4	Polyi-mide	Roger 5880	Neltec	FR4	FR4	Roger 5880
Height (㎜)	1.55	0.8	0.6	0.2	0.254	0.762	0.8	N/A	0.127
No. of resonance	6	1	3	3	3	4	2	2	5
No. of switch	6	N/A	2	N/A	1	2	N/A	N/A	1
Bandwidth (㎒)	1,400; 4,600	1,210	N/A	690	980; 1,200; 2,170;	100;330; 620;790;	244; 1,575	245; 525; 575	480;670; 900;2,760; 5,300

IV. CONCLUSION

In this thesis, a novel slotted patch multiband frequency-reconfigurable antenna has been designed to cater to various wireless communication applications, encompassing WLAN, X-band, and supporting SpaceX communication requirements. The adaptability and versatility of this antenna design allow seamless operation across multiple frequency bands, presenting an invaluable asset across diverse communication landscapes.

The core innovation of this antenna lies in its ability to dynamically adapt its frequency response, achieved through the integration of a switch within the radiator structure, enabling effective manipulation of its electrical length. This breakthrough in frequency agility unlocks the antenna's capacity to swiftly accommodate varying communication standards and frequency allocations demanded by different wireless communication protocols. Comprehensive analysis encompassing both SW-ON and SW-OFF conditions has been rigorously conducted, focusing on crucial performance metrics such as reflection coefficient, gain, efficiency, and detailed 2D and 3D radiation patterns. The meticulous comparison between simulated and measured reflection coefficients revealed a remarkably close agreement, signifying the robustness and accuracy of the proposed design. Furthermore, the antenna showcased efficient radiation characteristics across the five desired frequency bands, reinforcing its suitability and efficacy for upcoming and evolving communication systems. The consistent and reliable performance observed across these crucial frequency ranges positions this design as an optimal choice, potentially influencing and shaping the architecture of future wireless communication infrastructures. The successful implementation of this slotted patch multiband frequency-reconfigurable antenna not only addresses the immediate needs of diverse wireless communication applications but also lays a foundation for the evolution and enhancement of communication systems, offering a promising trajectory towards increased adaptability and efficiency in modern wireless technology.

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