SSRG International Journal of Electronics and Communication Engineering
ISSN: 2348-8549/ https://doi.org/10.14445/23488549/IJECE-V11I10P117

Volume 11 Issue 10, 211-226, October 2024

Original Article

Multifunctional Frequency Reconfigurable Antenna Array for Future Wireless Communication

Vinaya Deshmukh[1], Suvarna Chorage[2]

[1]*Department of E&TC, AISSMS Institute of Information and Technology, Maharashtra, India.*
[2]*Department of Electronics and Telecommunication, Bharati Vidyapeeth's COE for Women, Maharashtra, India.*

[1]*Corresponding Author : vinayadeshmukh2020@gmail.com*

Received: 17 August 2024 Revised: 18 September 2024 Accepted: 17 October 2024 Published: 30 October 2024

***Abstract* -** *The paper demonstrates a frequency-reconfigurable antenna array with multifunctional and multi-band operations. The integration of the PIN diode allows frequency reconfigurability. The diode ON and OFF condition for the antenna demonstrates two operating modes, one with six operating bands (3.68/5/6/7.79/9.87/12.19) while the other mode supports 3 operating frequencies (4.64/5.9/9.84). The design satisfies the bandwidth requirements with S11 < -10 dB and VSWR < 2. The antenna supports Narrowband and wideband operations. The single element to multielement configuration caused improvement in the fundamental parameters like Gain, return loss (S_{11}), VSWR, radiation properties (pattern), etc. The application areas for the proposed antenna include cognitive radio, MIMO, and S and C Band Microwave engineering.*

***Keywords* -** *Frequency Reconfigurable, Cognitive Radio (CR), PIN diode, Multiple Input, Multiple Output, Ultra-Wide Band.*

1. Introduction

An antenna plays a critical and crucial part of the communication system. The progression in wireless technology and semiconductor devices lead to the invention of various approaches to antenna design. The conventional antenna design approach exhibits many disadvantages. The most significant one is that the traditional antennae design for given system specifications became redundant with changes in certain operating parameters. As a known fact, the frequency spectrum meant for wireless communication is finite and becoming scarce due to the ever-increasing demand imposed on it. According to the experiment by the wireless regulator body FCC to determine the efficiency of spectrum utilization, 85% of the spectrum is underutilized. Spectrum utilization can be improved by making the system flexible according to the changes in the surrounding environment, which is the primary requirement of future wireless communication applications.

The best example is Cognitive Radio (CR), which has no static allocation channels. Everyone can use the licensed band based on some agreement between the primary and secondary users. In CR, the channels for the secondary users are allocated dynamically as per the user's requirements and with consent from the primary user. The primary users, licensed users, are authorized to use the allocated frequency spectrum. A multifunctional reconfigurable antenna with a multiband operation that can modify its operational parameters like frequency, polarization, or radiation pattern has become the prime requirement for present-day wireless systems. The future wireless era needs reconfigurable systems where the hardware is reconfigurable. Reconfigurability in antennae can be of three types: frequency, pattern, or polarization. Or it can be a hybrid combination of all three. Reconfigurability in the antenna can be achieved by incorporating semiconductor switches like Micro-Electro-Mechanical System (MEMS) switch, PIN diode, and varactor diode.

The Literature demonstrates many examples of frequency reconfigurable antennas, but there were major research gaps identified while the investigation was undertaken, which include:

- Complex antenna geometry utilized while exploring reconfigurability features
- Extensive use of semiconductor elements like PIN diodes, Varactor diodes, and RF-MEMS with the associated composite biasing circuits
- Significant impact and interference on the performance of the antenna due to the complex Biasing circuits

The proposed work demonstrates a simple antenna trying to minimize the use of external components to achieve frequency reconfigurability. This paper describes an approach for antenna design, wherein without altering the feed location and the antenna physical geometry, a multiband frequency reconfigurable antenna is obtained. As the antenna length determines the resonance frequency, a change in resonance frequency can be achieved by varying the effective antenna length. The aim is to design an antenna for wireless communication systems for future applications that is flexible or precisely reconfigurable with Multifunctional and multi-band characteristics and satisfies all the required antenna performance parameters.

The paper is structured as Section II explores the literature survey while Section III explains the methods used for antenna design and the corresponding equivalent circuit. Section IV highlights the results, which include the simulated and measured results, along with parametric analysis followed by a conclusion and references.

2. Literature Review

The [1] uses a varactor diode to implement an antenna to demonstrate a 15% adjusting range with but a complicated biasing circuit. A reconfigurable antenna with MEMS, a patch with slots, and the ground plane for quad-band operation are presented in [2] for the MIMO application. In [3], Four PIN diodes are incorporated into a forked-shaped antenna to achieve frequency and pattern reconfigurability. Ultrawideband (UWB) antenna with defective ground structure together with PIN diodes is exhibited in [4] with multiband frequency reconfigurable operations. Coplanar waveguide-fed antenna [5] is operational for eight frequency bands, frequency reconfigurability is achieved using 2 PIN diodes. A MIMO antenna [6] has a four-element configuration, and CPW fed demonstrates wideband performance with improved isolation and bandwidth. Literature reveals [7-15] extensive use of PIN diodes as a choice to attain frequency reconfiguration.

A two-element array using a varactor diode for frequency and pattern reconfigurability for the frequency range 2.15 to 2.38 GHz is presented in [16]. In [17], an antenna with an embedded biasing circuit to drive the PIN diodes to achieve multiband operations and frequency reconfigurability is presented. Elaborates the influence of slots and slits on the low-profile patch antenna with its mathematical analysis. The existing literature holds many examples of frequency reconfiguration achieved using different mechanisms (RF-MEMS, Varactor diode, PIN diode, etc.), but with more complexity and more PIN/ Varactor diodes used to achieve the desired results, causing the system to experience the impact of the biasing circuit associated with the PIN diode. The literature describes many such methods of implementation [5, 9, 11, 12, 14] and [18], and many more are enlisted in reference. The usability of antennas with reconfigurability for MIMO applications has been explored in literature by many researchers. In [20] 2x2 MIMO reconfigurable antenna with a varactor diode to support frequencies 1.78 GHz and 2.15 GHz, the antenna demonstrates narrow bandwidth using a very complex biasing circuit for a varactor diode. A slotted MIMO antenna in [21] supports the sub-6 GHz band, the design proposed doesn't support any reconfigurability, but in [22] a MIMO antenna with frequency reconfigurability for the fifth generation is proposed. A 2 x2 MIMO compact Vivaldi antenna for return loss -9dB in [23] explores up to X band but with the limitation of lack of reconfigurability. The antenna inherits poor isolation between the 2 ports, and DGS was introduced for isolation improvement. A complex-designed frequency reconfigurable antenna in [24] for Cognitive radio applications supports 3.25 GHz and 4.1 GHz.

The use of twelve PIN diodes complicates the design because each PIN diode requires its own biasing circuit, which impacts the performance. To increase the antenna results, metamaterials are used in [25], along with the integration of a PIN diode for frequency reconfigurability. A vertically suspended patch antenna to the ground plane is proposed in [26], and varactor diodes demonstrates the frequency tuning of the reconfigurable antenna between 3.3 and 4.2 GHz.

Twelve SMP1345-079LF PIN diodes used for a multiband reconfigurable antenna [27], the number of diodes is a potential issue in the design. [28, 29] explains antenna with Frequency reconfigurability for IoT, LTE, WiFi, and LTE applications. The use of paper material as substrate in frequency reconfigurable antennae in [30] with the two PIN diodes demonstrates an antenna for wearable applications. Similarly in [31], a simple rectangular frequency reconfigurable antenna for triple band operation in [32] with a band-stop filter is designed for cognitive radio applications. The impact of the parasitic patch on the performance of the radiating patch incorporated with the PIN diode is demonstrated in [33]. The usefulness of Frequency reconfigurable antennae in various applications and its importance is demonstrated in [34–36].

3. Methods: Antenna Design Procedures

The proposed novel reconfigurable antenna is implemented in a High-Frequency Structure Simulator (HFSS software). Various integrated features of HFSS include optometric analysis, integration of PIN diode as lumped RLC on the antenna radiating surface, radiation pattern, and current distribution visualization on the antenna geometry. Designing an antenna with a flexible RF front-end is the solution that drew the interest of many researchers. Figure 1 elaborates the application areas for frequency reconfigurable antennas. The proposed research paper focuses on designing an antenna array that is Multi-function, Multi-band, and frequency reconfigurable. It has acceptable antenna performance parameters, i.e., Gain, Return Loss (S_{11}), VSWR, radiation pattern, etc. The design process includes parametric analysis of the various antenna design parameters, i.e., Patch Length and width, length and width of the slots, and slits inserted, while making sure the antenna fundamental parameters, i.e., VSWR, S11, Radiation pattern, and frequency of resonance are within the acceptable limits.

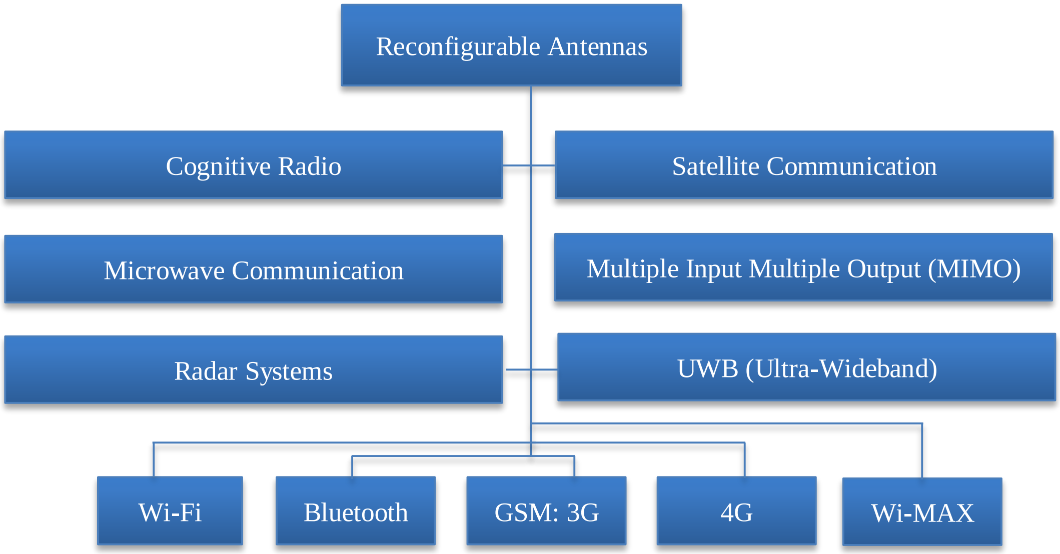


Fig. 1 Application areas

3.1. Design Approach for Frequency Reconfigurable Antenna Array

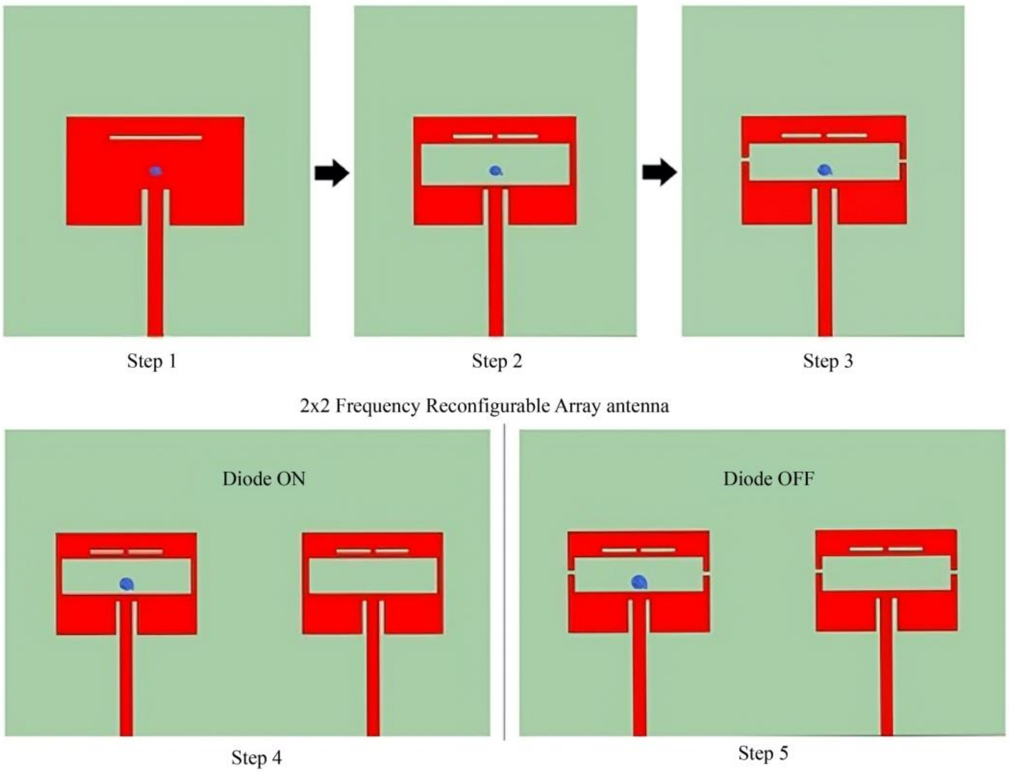


Fig. 2 The progression of the proposed 2 x 2 array configuration

Figure 2 explains the iterations of the suggested antenna. Through the extension of the job done in, the current effort demonstrates the multielement approach for MIMO applications, i.e. Multiple Input Multiple outputs. The reference antenna in Step 1 is a planar Microstrip antenna designed for 2.4 GHz, further, A slot was etched on the radiating patch, and the impact of the same was investigated. In Step 2 and Step 3, several slots were outlined on the radiating surface. The transmission line Model is used for the antenna analysis with the width of the antenna (W), Effective dielectric constant ($^{\varepsilon}$eff), Correction (ΔL), effective length of the patch (L_{eff}), and Actual patch length (L). The standard design Equations (1-5) are used for the proposed antenna from [19].

$$W = \frac{c}{2f_r\sqrt{(\varepsilon_r+1/2)}} \tag{1}$$

$$\varepsilon_{eff} = \frac{(\varepsilon_r\ +1)}{2} + \frac{(\varepsilon_r\ -1)}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{2}$$

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \tag{3}$$

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \tag{4}$$

$$L = \frac{c}{2f_r\sqrt{(\varepsilon_{eff})}} - 2\Delta L \tag{5}$$

The Resonant Frequency due to L_{eff} is given in Equation (6),

$$F_r = \frac{c}{2L_e\sqrt{\varepsilon_{eff}}} \tag{6}$$

A standard patch antenna for 2.4 GHz is used as a reference with dimensions 38 x 29.4 x 1.5 mm, FR4 dielectric constant (4.4), and an inset feed for better impedance matching. The reference antenna was loaded with slots, as shown in Figure 2, to achieve multi-resonance, the results of which are shown in Table 1 and Figure 3. Parametric analysis was done to calculate the optimum dimensions of the slots up until the anticipated results were accomplished.

Slots/slits or using Defected Ground Structures (DGS), which are also referred to as reactive loading, are used in the proposed antenna. Loading the radiating patch with slots strongly modifies the resonant mode of the radiator as the electric current path is altered, causing the antenna to exhibit more than a resonant frequency.

Parametric analysis of the same was undertaken to determine the optimum dimension for length, width, and slot location. Two semiconductor devices, i.e. PIN diodes, were used along with slots to realize frequency reconfigurability. Figure 4 depicts the position of PIN Diodes along the non-radiating edges.

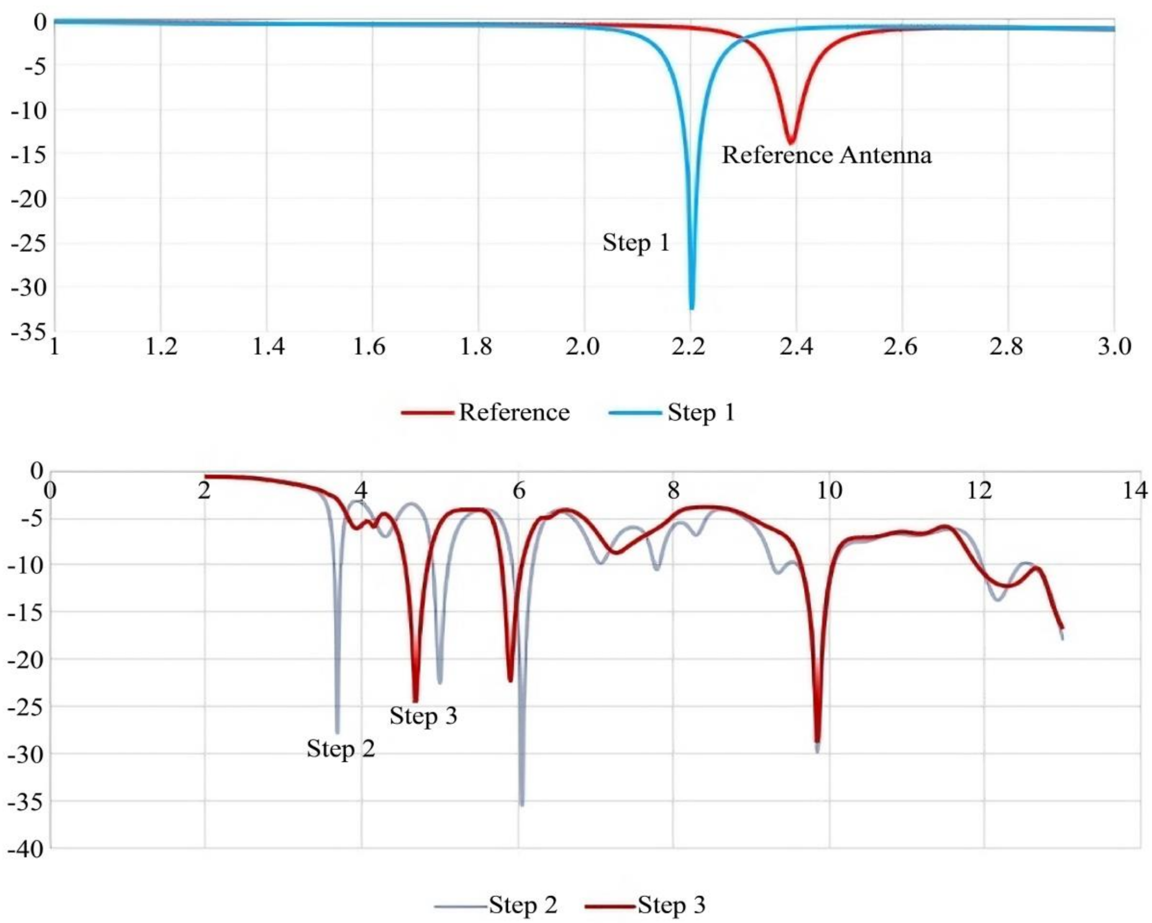


Fig. 3 Multi-resonance achieved in Step 1, Step 2, and Step 3

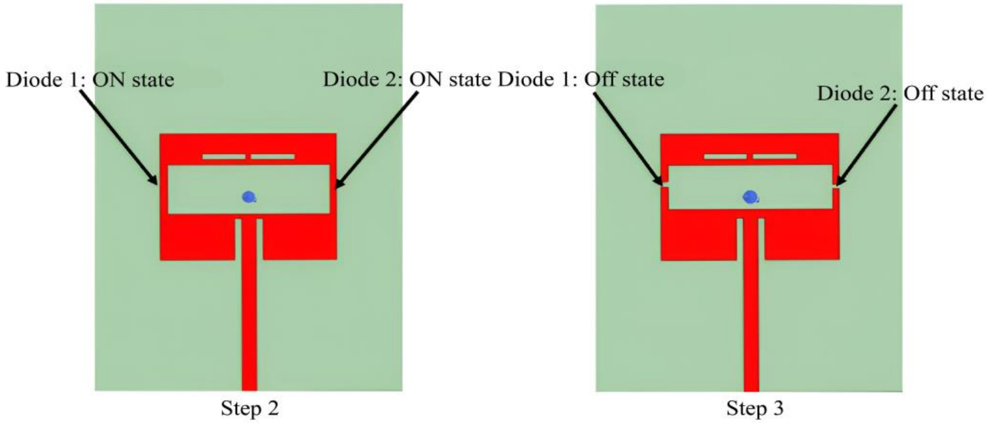


Fig. 4 (a) Microstrip patch antenna with dual Slot (MPADS)-Diodes ON, and (b) Microstrip patch antenna with dual Slot (MPADS) - Diodes OFF.

Table 1. Results for Step 1 to Step 3

Antenna Stages	F_r (GHz)	S_{11} (dB)
Reference antenna	2.3911	-14.48
Step 1	2.1733	-27.033
Step 2	3.686	-21.33
	5.00	-22.62
	6.08	-28.74
	7.79	-10.266
	9.87	-30.94
	12.19	-13.8
Step 3	4.64	-24.01
	5.935	-20.20
	9.8467	-25.168

3.2. Diode Circuit Modelling

MPADS with Diodes, both single and multielement, is conceived and modelled using ANSYS HFSS 18.0. The BAP65, 02-115 series PIN diode is considered for the design, equivalent circuit, along with its RLC lumped values depicted in Figure 5.

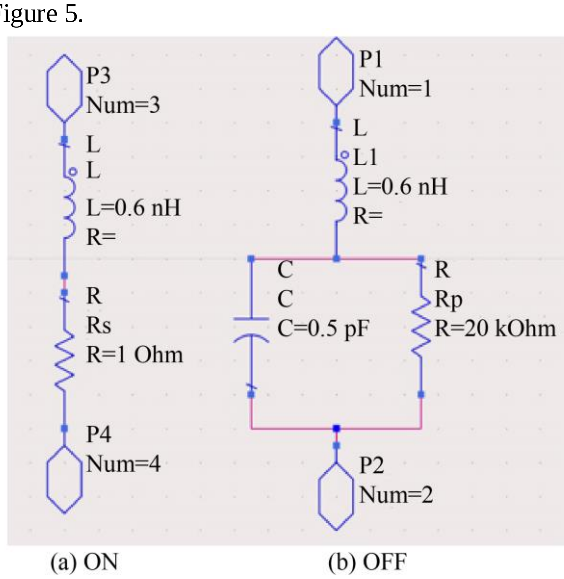


Fig. 5 Equivalent circuit for BAP65, 02-115 (a) ON state, and (b) OFF state.

The physical realization of the PIN diode, i.e., the ON condition on the fabricated antenna, is considered an ideal shot, and the Off condition is an Ideal Open.

3.3. Impact of the Insertion of Slots on the Radiating Surface of the Antenna

The compact antenna design was investigated for the impact of slots of various lengths and widths along with their position and the electronic semiconductor device, i.e., the PIN diode. In the simulation, it's considered as Lumped RLC.

The radiating patch loaded with multiple slots alters the current distribution path, causing the path length associated with the current vector to increase. As the resonance frequency of the antenna and the antenna length are inversely proportional to one another, an increase in the current path reduces the resonance frequency shown in Figure 6.

For DON, the effective length is increased, causing the frequency of resonance (Fr) to reduce to 3.686 GHz. While for DOFF Fr is 4.64 GHz.

The current density is concentrated towards the slot, as illustrated in Figure 7. Figure 8 and Figure 9 show the significance of the semiconductor device, i.e. PIN diode ON and OFF condition; the return loss better than -10 dB is observed with multi-band operation.

With the insertion of slots and the mode of the PIN diode, i.e. either ON or OFF, the effective length is changed, causing the antenna to have multiple resonances. Multi-band, Multifrequency, Multifunctional characteristics.

Single-element or multielement configuration allows for achieving a novel compact antenna with six operating frequency bands (3.68, 5, 6, 7.7, 9.8, 12) GHz. The antenna demonstrates good impedance attributes in multi-mode operation.

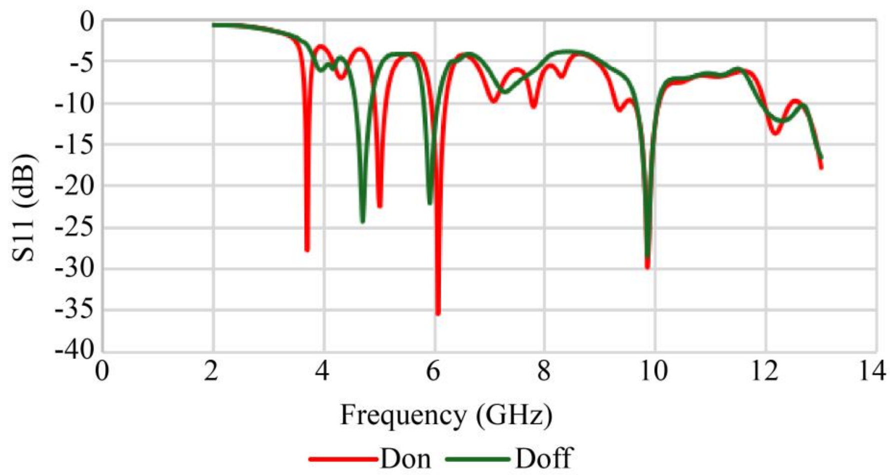
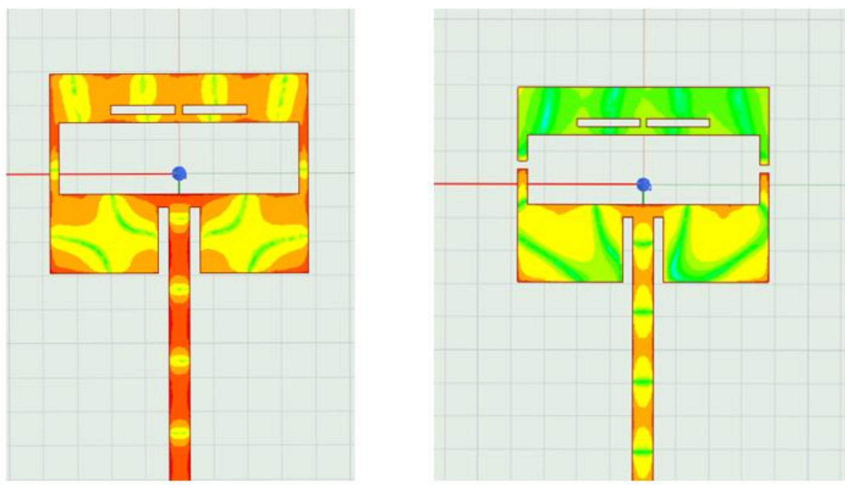
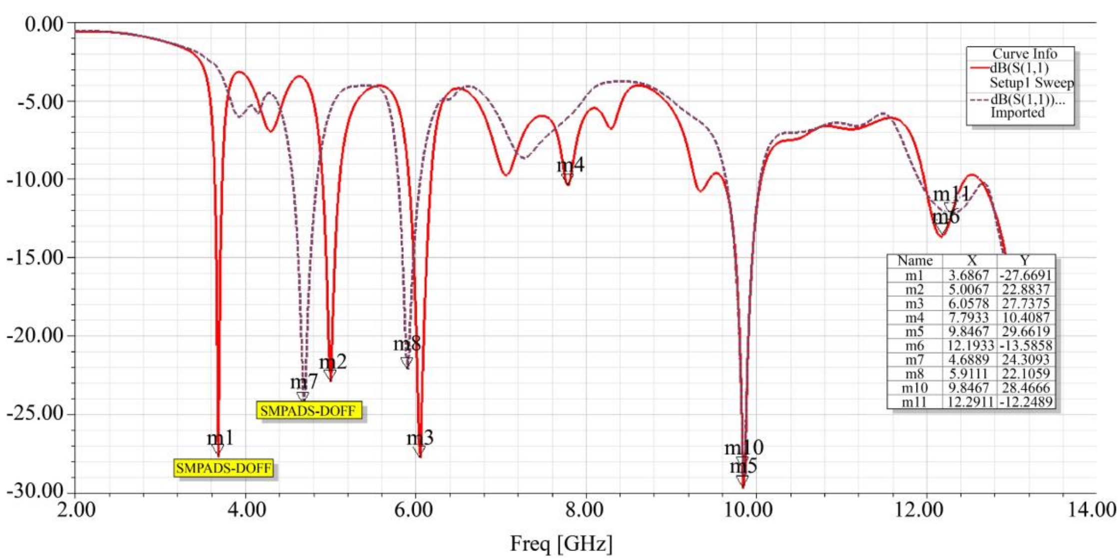


Fig. 6 Frequency vs S_{11}



(a) **(b)**

Fig. 7 Current distribution on the microstrip patch loaded with slots: (a) DON, and (b) DOFF.



Name	X	Y
m1	3.6867	-27.6691
m2	5.0067	22.8837
m3	6.0578	27.7375
m4	7.7933	10.4087
m5	9.8467	29.6619
m6	12.1933	-13.5858
m7	4.6889	24.3093
m8	5.9111	22.1059
m10	9.8467	28.4666
m11	12.2911	-12.2489

Fig. 8 Return loss for SMPADS Diodes ON and Diodes OFF

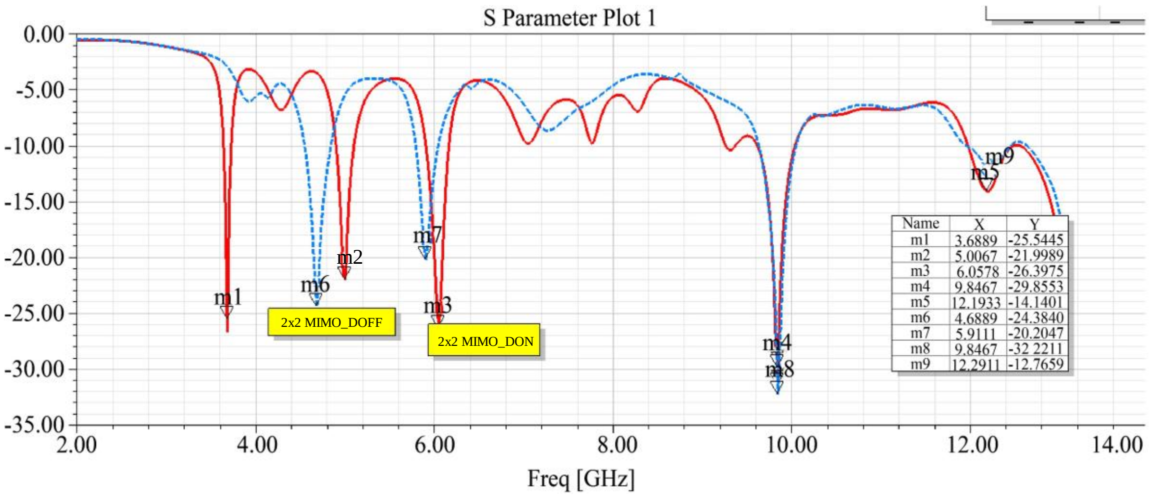


Fig. 9 Return loss for 2x2 array configuration diodes ON and diodes OFF

3.4. Equivalent Circuit Modelling for SMPADS

The discontinuity introduced due to the PIN diode's slots, and the ON/OFF situation alters the electric field distribution, which can be represented in terms of equivalent capacitance and the change in the magnetic field by equivalent inductance. The changes in the characteristics of the transmission line are represented in terms of Capacitance and Inductance. Figures 10 and 12 replicate the equivalent circuits in terms of RLC circuits for Single-element Microstrip Patch Antenna with Dual Slots (SMPADS) for DON and DOFF, respectively.

As the antenna demonstrates Multi-band characteristics, the equivalent circuit comprises cascading of several LC resonators. The impact is a multiband frequency response, depicting the expected resonance frequency achieved in simulation and the same in experimental observations Figures 11 and 13. The Lumped equivalent counterpart is realized using an Advanced Design System (ADS) circuit simulator. The ADS results are verified with the HFSS simulated results and antenna hardware Fabricated results.

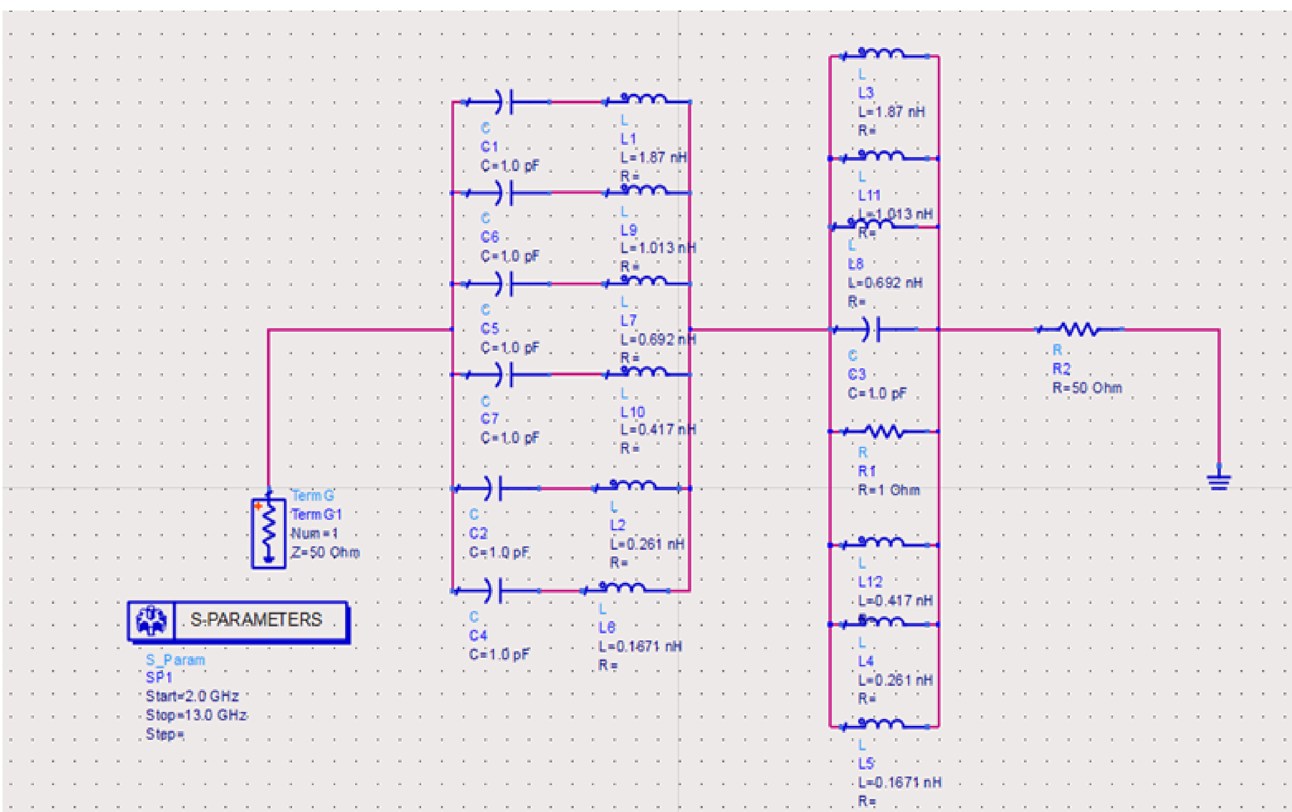


Fig. 10 Equivalent circuit for SMPADS-DON

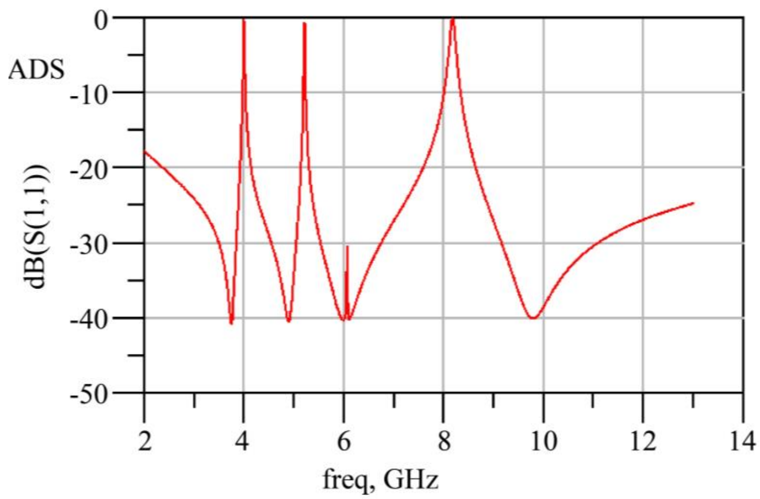


Fig. 11 Output of equivalent circuit for SMPADS-DON

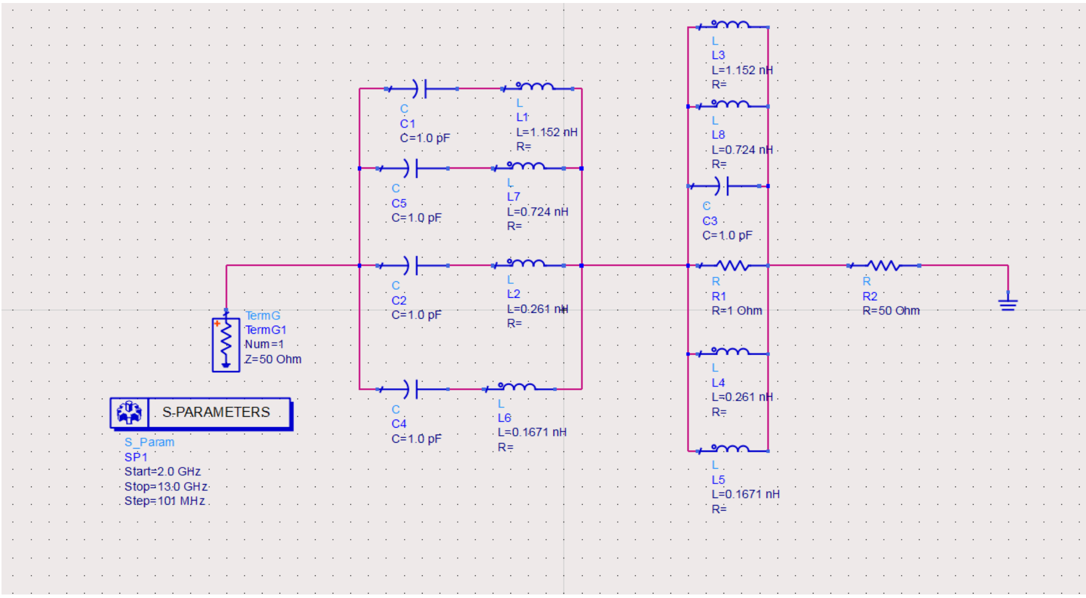


Fig. 12 Equivalent circuit for SMPADS-DOFF

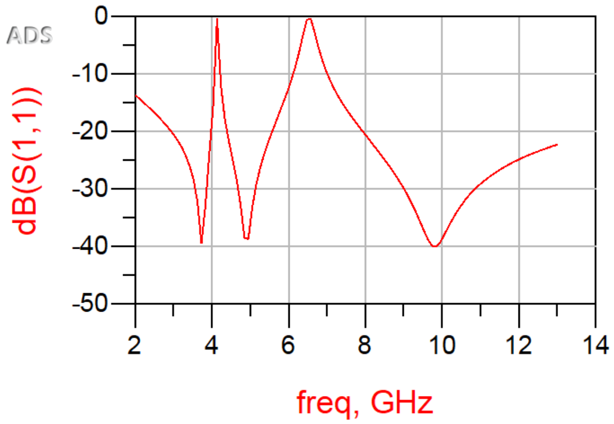


Fig. 13 Output of the Equivalent circuit for SMPADS-DOFF

4. Results and Discussion

The considerations for evaluating the antenna performance include VSWR, return loss (S_{11}), Frequency of resonance, Bandwidth, Radiation pattern, and Gain. The approach proceeds with analyzing the impact of multiple slots, slits, and semiconductor devices like PIN diode on the Microstrip antenna performance. The aim is to achieve a compact, Multifunctional, Multifrequency reconfigurable antenna with minimum devices or circuits. Table 2 summarizes the results of the investigation undertaken. Two approaches are taken: the first is a single element, and the second is multielement.

Following are the various versions of the antenna taken into consideration:

a) Single-element Microstrip Patch Antenna with Dual Slots (SMPADS) Diodes ON/OFF
b) 2 x 2 Array configuration with Diodes ON/OFF

Table 2. Summary of results for SMPADS-ON, SMPADS-DOFF, 2 x 2 array -DON, 2 x 2 array -DOFF

Design Stages	Simulated			Measured		
	Resonance Frequency (F_r) GHz	S_{11} (dB)	VSWR	Resonance Frequency (F_r) GHz	S_{11} (dB)	VSWR
SMPADS-DON	3.686	-21.33	1.19	3.64	-15.0	1.413
	5.00	-22.62	1.18	5.23	-17.5	1.359
	6.08	-28.74	1.10	6.14	-14.7	1.492
	7.79	-10.266	1.8	7.76	-18.29	1.287
	9.87	-30.94	1.05	9.32	-14.36	1.478
	12.19	-13.8	1.5	12.93	-17.00	1.325
SMPADS-DOFF	4.64	-24.01	1.14	4.655	-22.8	1.179
	5.935	-20.20	1.21	5.91	-16.77	1.395
	9.8467	-25.168	1.11	9.74	-25.818	1.5
2 x 2 ARRAY-DON	3.68	-22.88	1.16	3.62	-12.985	1.5
	5	-22.40	1.22	4.98	-15.225	1.42
	6	-28.11	1.1	5.93	-14.887	1.204
	9.85	-28.48	1.08	9.6	-18.519	1.201
	12.19	-13.9	1.5	12.17	-24.085	1.205
2 x 2 ARRAY-DOFF	4.713	-23.53	1.14	4.64	-15.83	1.3
	5.93	-19.78	1.12	5.82	-18.75	1.2
	9.87	-26.51	1.09	9.86	-13.43	1.5
	12.26	-12.59	1.6	12.19	-27.35	1.19

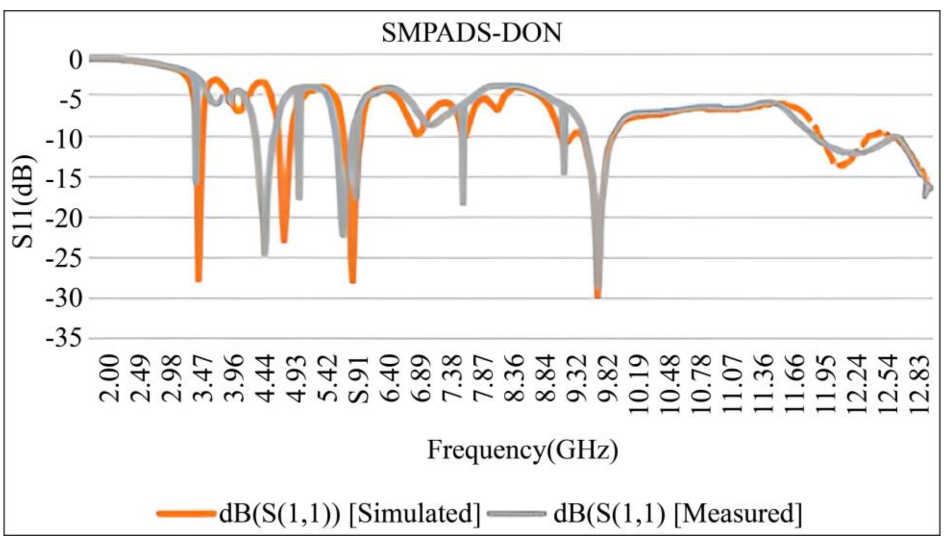


Fig. 14 Comparison of simulated and measured results for SMPADS-DON

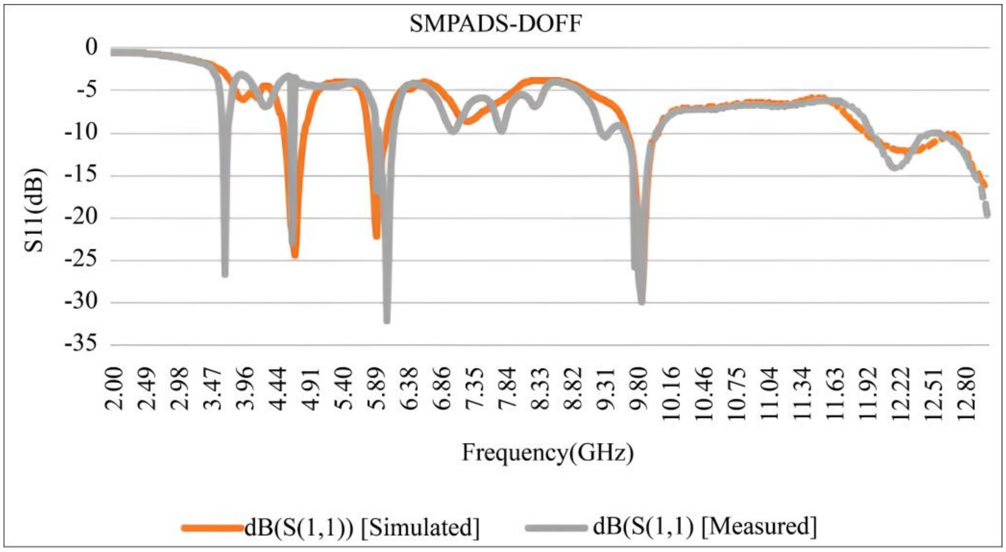


Fig. 15 Comparison between simulated and measured results for SMPADS-DOFF

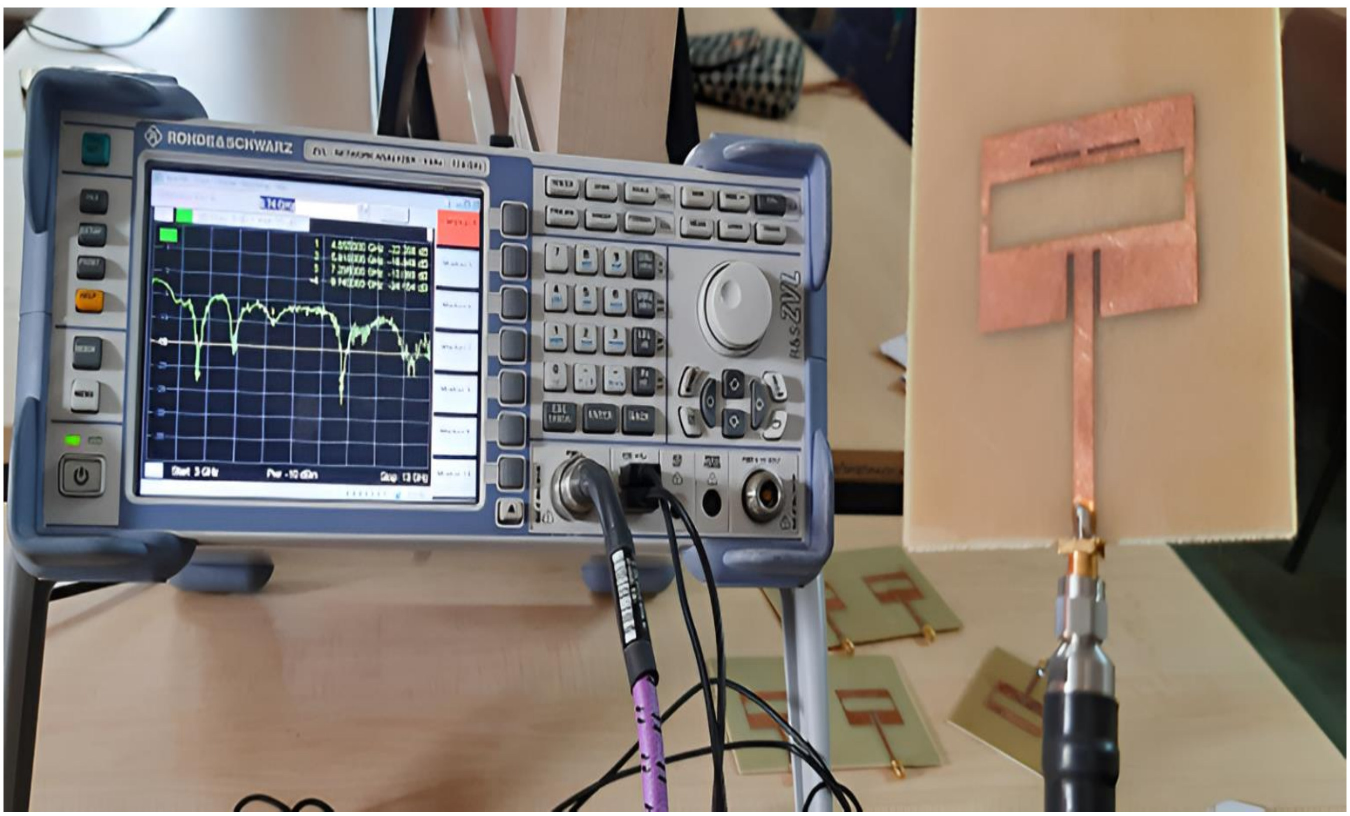


Fig. 16 VNA interfaced with the antenna

The antenna testing was done using the Rohde & Schwarz vector network analyzer. The HFSS simulated and experimentally measured results show decent accord, as shown in Figures 14 and 15. The experimental setup for antenna testing is shown in Figure 16. The radiation pattern of the recommended antenna is indicated in Figure 17, which illustrates a directional pattern with an appropriate Gain of 2 dB. This observation is for single-element configuration. As shown in Figures 16 and 19. Demonstrates the complete measurement setup using a Vector Network Analyzer (VNA). The VNA supported frequency specifications up to 13 GHz.

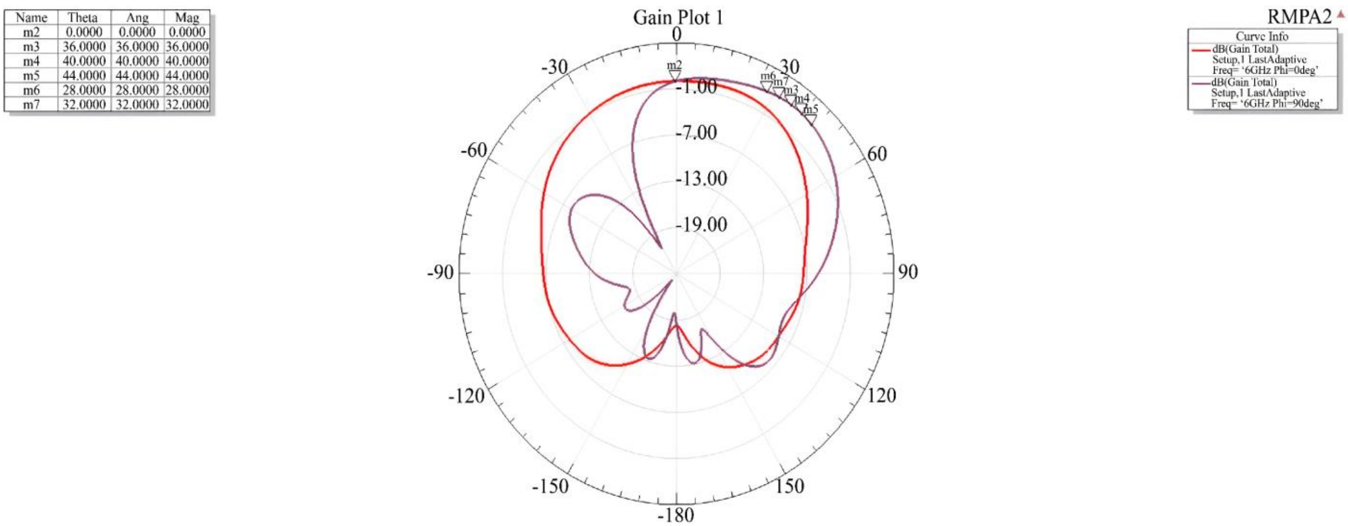


Fig. 17 Gain for SMPADS with Diodes condition OFF

Improvement in Gain (4dB) and a directional pattern is achieved for multielement configuration, as shown in Figure 18 and the experimental setup in Figure 19. For any good MIMO antenna, we know that $|S_{21}| \approx |S_{12}|$ and the mutual coupling among the antenna should be below -20 dB. The 2x 2 array configuration applies to MIMO applications as the mutual couple threshold is -44.013 dB, as shown in Figure 20. The 2x2 MIMO configuration has good isolation and accord between the measured and simulated results. The Identical SMPADS are placed linearly, and the spacing between them is optimized for better isolation. The isolation achieved is greater than 20 dB for the desired frequency of operations.

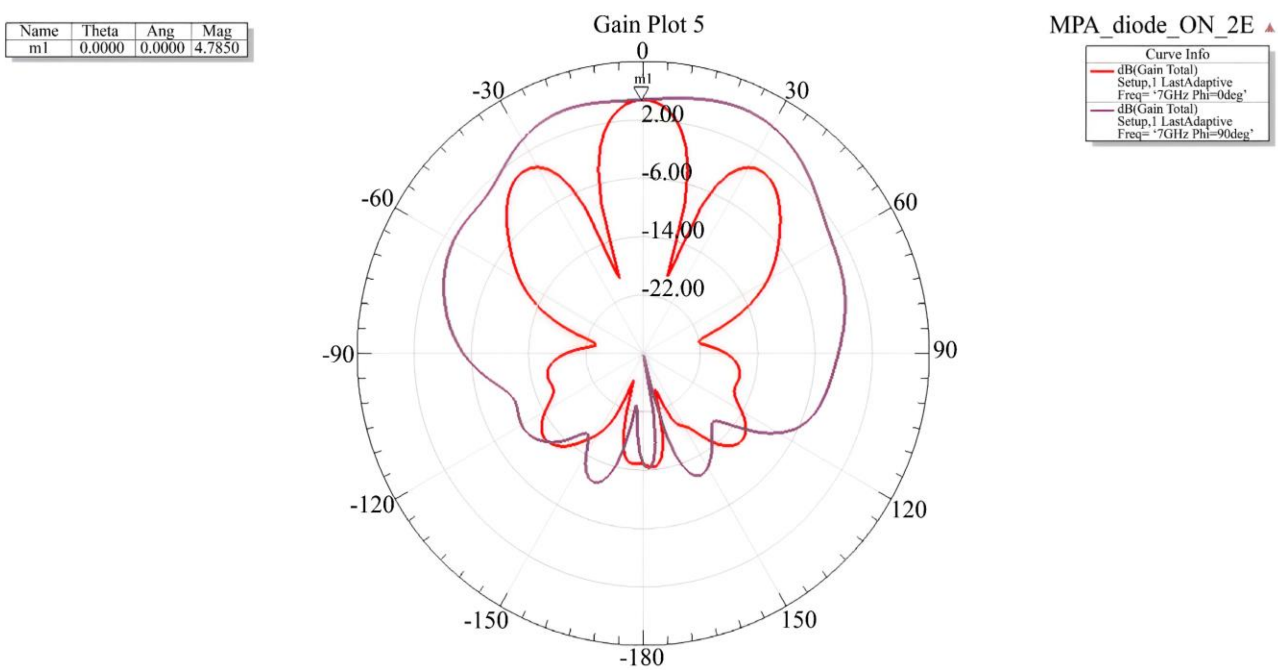


Fig. 18 2x2 array antenna gain for DON

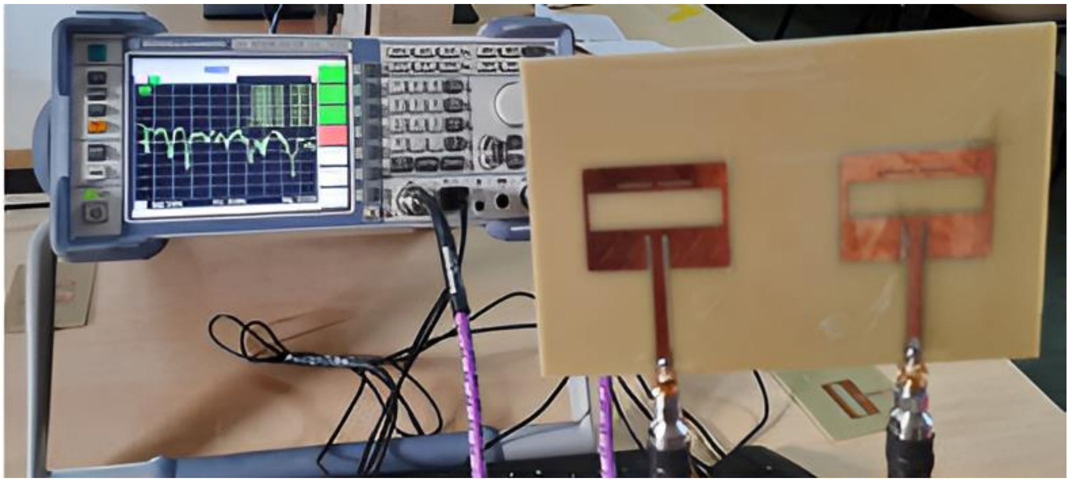


Fig. 19 VNA interfaced with the antenna

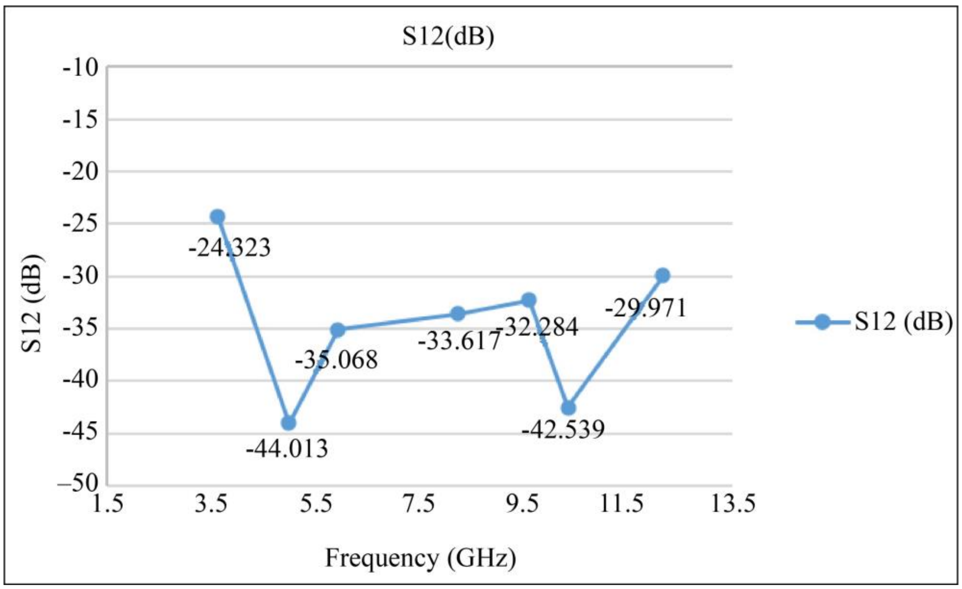


Fig. 20 S12 for 2x2 array for MIMO application

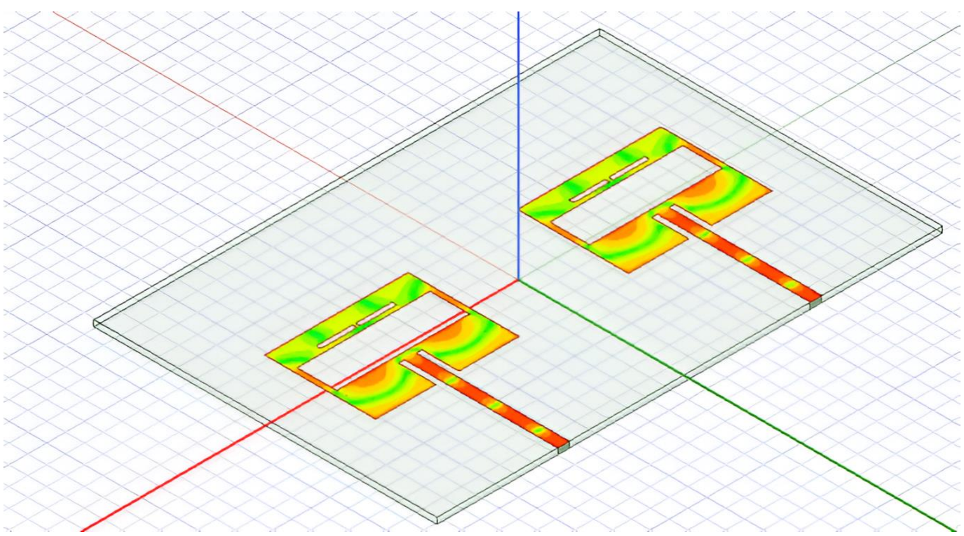


Fig. 21 Current distribution

5. Parametric Analysis Procedure

The miniatured, simple, low-profile antenna is optimized for operation up to 12 GHz. The initial configuration of a simple inset feed microstrip patch for 2.45 GHz was transformed into a reconfigurable antenna by the addition of slot resonators and PIN diode., which also enabled the attainment of multifrequency and multiband operation from 3.68 GHz to 12 GHz. Parametric analysis was done to determine the appropriate width, length, and position of the slots inserted on the radiating patch. Demonstrates the parametric analysis for Slot_1, while the present work emphasizes the optimization of Slot_2; both slots are referred to in Figure 22.

The Slot_2 Length was varied from 4.5mm to 11.5mm in step of 1mm. The L_slot_2 for 10.5mm demonstrates good impedance matching, with return loss less than -10dB and VSWR less than 2. The optimized length and width for Slot_2 L_slot x W_slot are 10.5mm x 35.2 mm, and the results achieved for S11 and VSWR are acceptable. Figure 23 explains the parametric analysis performed to determine the optimum length of Slot_2. The length of Slot_2 was varied from 4.5 mm to 11.5 mm in the step of 1mm.

Table 3 highlights the comparison of the proposed SMPADS with other shared work available in the literature. The comparison distinctly explains the improvement in the proposed work, the dual mode of operation covering S, C, and X bands, and good impedance matching.

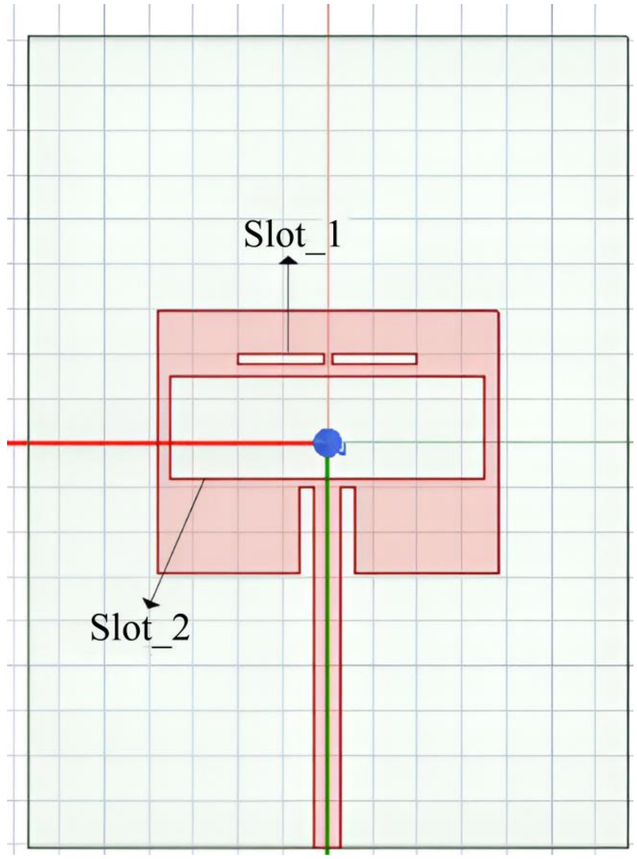


Fig. 22 Microstrip antenna with Slot_1 & Slot_2

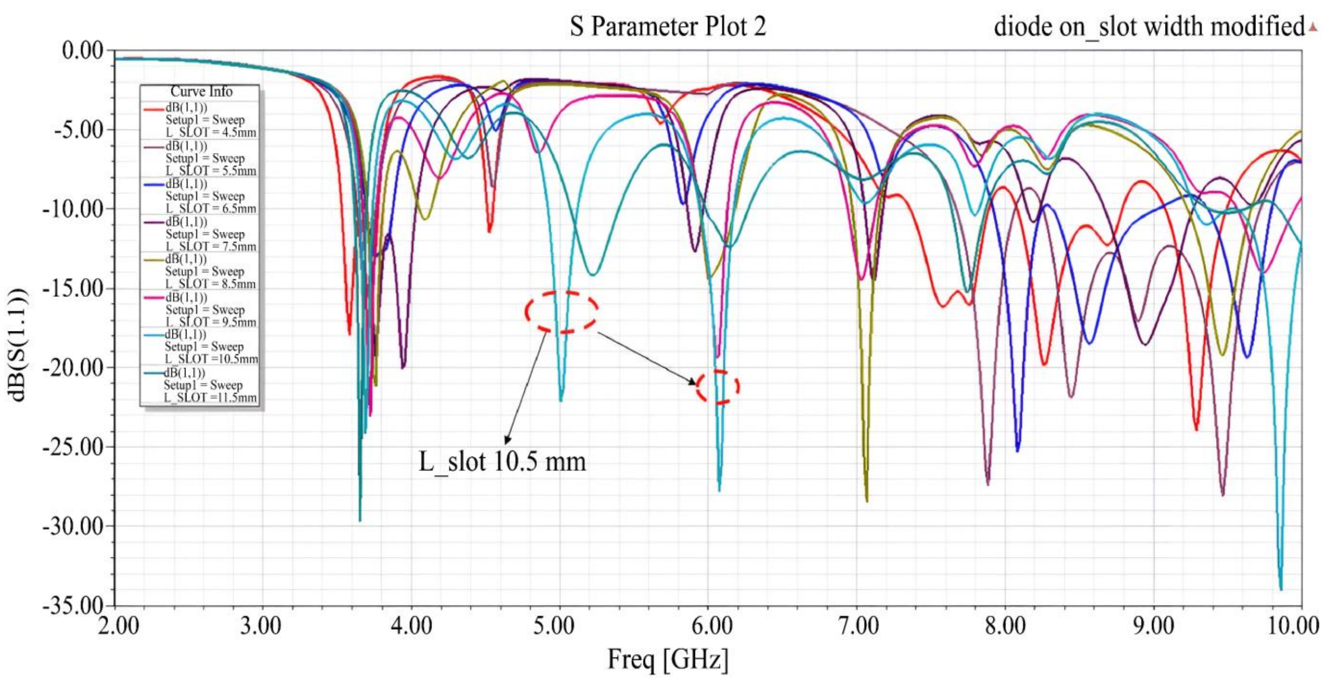


Fig. 23 Parametric analysis for variation in L_slot from 4.5mm to 11.5mm in steps of 1mm

Table 3. Comparison of the proposed frequency reconfigurable antenna (SMPADS) with other related work

Reference	Dimensions (mm)	Actuators	No. of Actuators	Frequency Bands	Comment
[1]	22 x 21x1.6	Varactor diode	1	1000-1150 MHz	Biasing circuit complexity, variation in voltage from 0.0-7.5 V is required to achieve the required frequency shift.
[2]	32 x 92 x 1	RF-MEMS	1	600 MHz, 1.8, 2.4, 3.5, and 5.5 GHz bands	Costlier due to the use of RF-MEMS
[3]	29 x 23 x 1.6	PIN diodes	4	3, 3.1, 3.2, 3.72, 4.9, 5, 5.2, and 5.5 GHz,	Biasing circuit complexity due to the use of four PIN diodes.
[4]	47 x 37 x 1.6	PIN diodes	3	1.36, 1.8, 3.0, 3.9 , 5.0, 6.2, 6.4, 7.4, 7.9, 8.2, 8.4, 8.6 GHz	Biasing circuit complexity due to the use of three PIN diodes.
[7]	40 x 48 x 1.6	PIN diodes	2	3.97,5.28,6.48,8.59,9.06	The paper demonstrates only the pin diode modeling and design using HFSS, and biasing circuit implementation is missing.
[8]	45 x 40 x 1.6	PIN diodes	6	1.5 - 2.9	Realization of the six switches are as metal Bridges; the absence of the metal bridge is treated as OFF while the presence is ON.
[9]	120 x 120 x 1.575	PIN diodes	3	1.1753 GHz and 2.4895 GHz	PIN diode modeling is explained in HFSS, but PIN diode physical realization is not demonstrated.
[10]	28 x 22 x 1.6	PIN diodes	3	2.45, 4.72, &7.41 GHz	Biasing circuit for three-pin diodes required
Proposed	38 x 29.4 x 1.6	PIN diodes	2	Mode1 (DON): 3.686, 5, 6.08, 7.79, 9.87, 12.19 & Mode2 (DOFF): 4.64, 5.9, 9.8	Compact size, a wide range of frequency bands supporting S, C, and X band applications

The proposed antenna holds lots of potential for next-generation wireless communication applications. The main motto was to achieve a frequency reconfigurable antenna that is multi-band and multifunctional and to return loss with a value better than -10dB and VSWR less than 2. The design is simple and low profile, yet lots of challenges were experienced, which included trying to maintain a simple antenna geometry satisfying the required specification without increasing the geometry complexity.

Initially tried the option of eliminating the use of the PIN diode. However, the results were not as expected, leading to the final approach of minimizing the PIN diode and minimum biasing components. Table 3 highlights the work achievements, with the minimum biasing circuit for the reduced number of PIN diodes.

HFSS allowed the simulation, verification, and validation of the process of PIN diode integration on the antenna radiating surface. The initial design was evaluated for the antenna with two approaches: 1) Ideal PIN Diode condition DON = Short and DOFF = Open 2) Integration of PIN diode as Lumped RLC. During the COVID condition, the PIN diode availability and procurement process were highly impacted, so the above approach was used. Later, PIN diode selection was made per requirements, i.e., frequency of operation, packaging, lead-time, Foort-print, and cost.

Wireless standards like 802.11 and 802.16, where the requirement for bandwidth varies from 20 MHz, 160 MHz, or 320 MHz, VSWR less than 2. The proposed antenna suits the above requirements with better and improved performance parameters. i.e. VSWR $\leq$ 1.5, which indicates better impedance matching and low reflection losses.

6. Conclusion and Future Work

The 2x2 Multi-band antenna array with frequency reconfigurability demonstrates improved performance parameters. The ON/OFF condition of the PIN diode allows the antenna to achieve frequency reconfigurability. In the Diode-ON condition, the antenna operates at six frequencies: 3.68 / 5 / 6 / 7.79 / 9.87 /12.19 GHz. For the Diode-OFF condition, the antenna achieves Triple band operation, i.e. 4.64 / 5.93 / 9.84 GHz. The design satisfies the bandwidth requirements with $S11 < -10$ dB and VSWR < 2.

The antenna shows a narrowband operation for most of the operating bands with the impedance bandwidth achieved to approx. 5% and few UWB operations. For example, in operating bands 6.05-5.08 GHz, the bandwidth achieved is 16.44%. The 2x 2 MIMO configuration shows better isolation greater than -20dB, with Gain being improved twice concerning single-element configuration. The antenna extends many prospects for future wireless applications, including IoT, Cognitive Radio, MIMO, and Satellite communications (S and C Microwave bands).

Acknowledgment

The author would like to thank the Dept. of E&TC, AISSMS IOIT College of Engineering, Pune, for extending support while completing the work.

References

[1] Mahmoud Al Ahmad et al., "Compact Single-Varactor Diode Frequency-Reconfigurable Microstrip Patch Antenna," *IET Microwaves, Antennas and Propagation*, vol. 15, no. 9, pp. 1100-1107, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[2] Muhammad Mateen Hassan et al., "Two-Element MIMO Antenna with Frequency Reconfigurable Characteristics Utilizing RF MEMS for 5G Applications," *Journal of Electromagnetic Waves and Applications*, vol. 34, no. 9, pp. 1210-1224, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[3] Poonam Thanki, and Falguni Raval, "Fork-Shaped Frequency and Pattern Reconfigurable Antenna," *International Journal of Communication Systems*, vol. 33, no. 17, pp. 1-11, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[4] M. Jenath Sathikbasha, and V. Nagarajan, "Design of Multiband Frequency Reconfigurable Antenna with Defected Ground Structure for Wireless Applications," *Wireless Personal Communications*, vol. 113, pp. 867-892, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[5] Wahaj Abbas Awan et al., "A Miniaturized Wideband and Multi-Band on-Demand Reconfigurable Antenna for Compact and Portable Devices," *AEU - International Journal of Electronics and Communications*, vol. 112, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[6] A.W. Mohammad Saadh et al., "A Uniquely Shaped MIMO Antenna on FR4 Material to Enhance Isolation and Bandwidth for Wireless Applications," *AEU - International Journal of Electronics and Communications*, vol. 123, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[7] Tayyaba Khan, and MuhibUr Rahman, "Design of Low-Profile Frequency Reconfigurable Antenna for Multiband Applications," *International Journal of Electronics Letters*, vol. 10, no. 1, pp. 30-47, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[8] Mohammad M. Fakharian, Pejman Rezaei, and Ali A. Orouji, "A Multi-Reconfigurable CLL-Loaded Planar Monopole Antenna," *Radioengineering*, vol. 29, no. 2, pp. 313-320, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[9] Minakshmi Shaw, and Yogesh Kumar Choukiker, "Frequency Reconfigurable Microstrip Patch Antenna for IRNSS Applications," *2020 International Conference on Inventive Computation Technologies (ICICT)*, Coimbatore, India, pp. 878-880, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[10] Manish Sharma, Vikas, and Naresh Kumar, "Design and Analysis of Frequency Reconfigurable Multiband Antenna (Bluetooth/Downlink Frequencies for INSAT/Downlink X-Band Satellite System) Using PIN Diodes for Wireless Communication Systems," *2020 IEEE International Conference on Computing, Power and Communication Technologies (GUCON)*, Greater Noida, pp. 90-94, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[11] Amjad Iqbal et al., "Frequency and Pattern Reconfigurable Antenna for Emerging Wireless Communication Systems," *Electronics*, vol. 8, no. 4, pp. 1-12, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[12] J. Kumar, B. Basu, and F.A. Talukdar, "Modeling of a PIN Diode RF Switch for Reconfigurable Antenna Application," *Scientia Iranica*, vol. 26, no. 3, pp. 1714-1723, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[13] Amjad Iqbal et al., "Low-Profile Frequency Reconfigurable Antenna for Heterogeneous Wireless Systems," *Electronics*, vol. 8, no. 9, pp. 1-11, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[14] I.A. Shah et al., "Design and Analysis of a Hexa-Band Frequency Reconfigurable Antenna for Wireless Communication," *AEU - International Journal of Electronics and Communications*, vol. 98, pp. 80-88, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[15] Jie Liu, Jianying Li, and Rui Xu, "Design of Very Simple Frequency and Polarisation Reconfigurable Antenna with Finite Ground Structure," *Electronics Letters*, vol. 54, no. 4, pp. 187-188, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[16] Siti Nailah Mastura Zainarry, Nghia Nguyen-Trong, and Christophe Fumeaux, "A Frequency- and Pattern-Reconfigurable Two-Element Array Antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 4, pp. 617-620, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[17] Adisak Romputtal, and Chuwong Phongcharoenpanich, "Frequency Reconfigurable Multiband Antenna with Embedded Biasing Network," *IET Microwaves, Antennas Propagation*, vol. 11, no. 10, pp. 1369-1378, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[18] Ashish Singh et al., "Analysis of Microstrip Line Fed Patch Antenna for Wireless Communications," *Open Engineering*, vol. 7, no. 1, pp. 279-286, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[19] Constantine A. Balanis, *Modern Antenna Handbook*, Wiley, pp. 1-1712, 2011. [Google Scholar] [Publisher Link]

[20] A. Raza et al., "A 2-Element Meandered-Line Slot-Based Frequency Reconfigurable MIMO Antenna System," *Microwave and Optical Technology Letters*, vol. 60, no. 11, pp. 2794-2801, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[21] Neetu Agrawal, Manish Gupta, and Sanjay Chouhan, "Modified Ground and Slotted MIMO Antennas for 5G Sub-6 GHz Frequency Bands," *International Journal of Microwave and Wireless Technologies*, vol. 15, no. 5, pp. 817-825, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[22] Puspendu Bikash Saha et al., "Frequency Reconfigurable Two-element MIMO Antenna for 3G/4G/5G Cellular Communications," *2021 IEEE Indian Conference on Antennas and Propagation (InCAP)*, Jaipur, Rajasthan, India, pp. 965-968, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[23] Rong Li et al., "A Compact Two-port Vivaldi-Based MIMO Antenna with High Isolation for C and X Bands Applications," *Progress in Electromagnetics Research Letters*, vol. 120, pp. 95-101, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[24] D.S. Aldar, "Frequency Selective Reconfigurable Microstrip Antenna for Cognitive Radio Applications," *Advanced Electromagnetics*, vol. 11, no. 4, pp. 60-68, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[25] S. Chetan et al., "Design and Performance Analysis of Multiband Patch Antenna with Metamaterial for Wireless Applications," *Indian Journal of Science and Technology*, vol. 17, no. 3, pp. 270-276, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[26] Jeen-Sheen Row, and Jun-Yan Chen, "A Novel Design for Frequency Reconfigurable Antennas," *Microwave and Optical Technology Letters*, vol. 64, no. 10, pp. 1815-1820, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[27] Ikhlas Ahmad et al., "A Pentaband Compound Reconfigurable Antenna for 5G and Multi-Standard Sub-6GHz Wireless Applications," *Electronics*, vol. 10, no. 20, pp. 1-16, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[28] Prem Pal Singh et al., "Frequency Reconfigurable Multiband Antenna for IoT Applications in WLAN, Wi-MAX, and C-Band," *Progress in Electromagnetics Research C*, vol. 102, pp. 149-162, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[29] Shreyas S. Bharadwaj et al., "A Compact Tri-Band Frequency Reconfigurable Antenna for LTE/Wi-Fi/Its Applications," *Progress in Electromagnetics Research M*, vol. 91, pp. 59-67, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[30] Ajit Kumar Singh et al., "Low-Loss Paper-Substrate Triple-Band-Frequency Reconfigurable Microstrip Antenna for Sub-7 GHz Applications," *Sensors*, vol. 23, no. 21, pp. 1-13, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[31] Alexandros Sakkas et al., "A Frequency-Selective Reconfigurable Antenna for Wireless Applications in the S and C Bands," *Sensors*, vol. 23, no. 21, pp. 1-16, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[32] Hashinur Islam et al., "A Frequency Reconfigurable MIMO Antenna with Bandstop Filter Decoupling Network for Cognitive Communication," *Sensors*, vol. 22, no. 18, pp. 1-24, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[33] Devendra Kumar, and Dhirendra Mathur, "Novel Design of a Bandwidth Enhanced and Frequency Reconfigurable, Wearable Antenna for Body Centric Communication," *Journal of Electromagnetic Engineering and Science*, vol. 24, no. 3, pp. 264-275, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[34] Caibiao Guo et al., "Variode-Enabled Frequency-Reconfigurable Microstrip Patch Antenna with Operation Band Covering S and C Bands," *Progress Electromagnetics Research M*, vol. 88, pp. 159-167, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[35] Younes Karfa Bekali et al., "A New Design for a Novel Compact Frequency Reconfigurable Antenna," *International Journal of Microwave and Optical Technology*, vol. 18, no. 4, pp. 320-329, 2023. [Google Scholar] [Publisher Link]

[36] Youcef Braham Chaouche et al., "A Frequency Reconfigurable U-Shaped Antenna for Dual-Band WIMAX/WLAN Systems," *Progress In Electromagnetics Research C*, vol. 87, pp. 63-71, 2018. [CrossRef] [Google Scholar] [Publisher Link]