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Design, Simulation and Mathematical Modelling of Slotted Microstrip Patch Reconfigurable Antenna Array for Future Wireless Communication

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Abstract:

A multi-slotted Microstrip frequency reconfigurable antenna is designed-simulated and analyzed in this paper for MIMO applications. The antenna demonstrates the impact of parasitic patches, Slots, and PIN diode on the radiating surface. Designed to operate at five frequencies 3.7 GHz/ 5 GHz/ 6 GHz /9.8 GHz with S11 < -10 dB and VSWR < 2. The communicating bands and the bandwidth achieved by the reconfigurable antenna are 3.72 - 3.8 GHz / 2.1% bandwidth, 4.89 – 5 GHz / 2.2% bandwidth, 5.85 – 6.28 GHz / 7.2% bandwidth, and 9.63 – 9.97 GHz / 3.4% bandwidth. The antenna holds potential applications in areas such as Cognitive radio, C and X band (Microwave communications), MIMO, WiMAX, Satellite Communication, etc.

Keywords: Reconfigurable antenna array, MIMO, WiMAX, cognitive radio, PIN diode

1. INTRODUCTION

Modern-day requirements for wireless devices are more demanding and require high standards. It's an era of Miniaturization, where each device demands to have an extremely compact size without compromising on performance. For antenna design, the size of the antenna, gain, frequency of operation, and radiation pattern are all factors that need to be considered. Present-day wireless communication systems demand support of more than one frequency and more than one application that is we can say multi-frequency, multi-application. Compact single antenna having multi-frequency, multi-band operation, and cognitive to changing requirements. This flexibility is possible with reconfigurable antennas, where the alteration of the antenna geometry is achieved either by using semiconductor devices like PIN diode, Varactor diode, or RF MEMS. Due to ease and affordability, the most frequently used approach for frequency reconfigurable antenna is incorporating a PIN diode.

Traditional Microstrip antenna has many restrictions which include narrow bandwidth, single frequency of operation, low or moderate gain, huge size, and issues with polarization. Various methods are employed to improve the fundamental parameters of the microstrip antenna which involves Metamaterials, various types of feeding methods, altering the antenna geometry by addition of semiconductor devices, or etching various geometrical shapes i.e. for example slots or slits on radiating surface or ground plane(Khandelwal, Kanaujia and Kumar, 2017). A varactor diode-based compact frequency reconfigurable antenna in (Al Ahmad *et al.*, 2021), demonstrates four designed microstrip patches that feed through coaxial feeding and are interconnected by a single varactor diode and a few metallic strips. Similarly, in (Shaw, 2020), a simple and compact frequency reconfigurable antenna for satellite application is presented, wherein, three PIN diodes are incorporated on the radiating Microstrip patch. In (Swathi, Ujjwal and Chilukuri, 2018) L and U-shaped slots are etched on the ground plane, underneath the radiating Microstrip patch, achieving Frequency reconfigurability using 3 PIN diodes with the multi-frequency operation. Four Pin diodes used to achieve frequency reconfigurability, with coplanar ground are demonstrated in (Liu, Yang and Kong, 2015).

The monopole antenna operates in three bands with diodes mounted on the ground surface. Similar work is presented by (Ghaffar, Li, Awan, *et al.*, 2020), (Ghaffar, Li, Hussain, *et al.*, 2020), and (Iqbal *et al.*, 2019) employing PIN diodes to achieve frequency reconfigurability, the radiating patch shape is triangular making it resonant for multiband and having multi-frequency capabilities. (Pant, Singh and Parihar, 2021) array configuration for reconfigurable antenna (MIMO antenna) for 5G applications. (Hussain *et al.*, 2022) Circular patch with a single PIN diode for frequency reconfigurability, along with a slot etched along its surface along with coplanar ground. In (Mansoul and Nedil, 2020) Compact slot 2-element MIMO antenna with six-pin diodes for frequency reconfigurability for triple band operation. UWB reconfigurable antenna (Badamchi *et al.*, 2014), with the radiating patch having multiple slots connected using PIN diodes supports dual-band operations. The use and impact of PIN diode, varactor diode, Parasitic patches, and DGS are demonstrated by (Khan et al., 2018; Mohamed and Zoubir, 2018; Abdi, Nourinia and Ghobadi, 2021; Kucukoner et al., 2021; Reji and Manimegalai, 2021; Aldar, 2022; Guerroui et al., 2022).

2. Antenna design procedures

The proposed work emphasizes the impact of various elements loaded on the microstrip antenna making it more flexible and at the same time reducing its size making it more compact. The various elements that are considered for evaluation include the slots and slits of different widths and lengths along with the appropriate location, which is loaded on the radiating patch, Defected ground structures (DGS), parasitic elements, and Semiconductor devices (PIN diode).

2.1 Design approach: Multi-element (Array) antenna

The antenna design and simulation were done in HFSS software. The parameters considered for the design include the length, width, and position of the radiating patch and the parasitic patches, and slot etched on the radiating patch. The Microstrip antenna is designed with an FR4 substrate with a dielectric constant of 4.4. The length (L) and width (W) of the antenna are optimized with multiple iterations to achieve the expected results. The microstrip patch has an inset feed or better impedance matching. The design approach is divided into a single-element approach and a multi-element approach with the diode condition ON or OFF. The main aim is to investigate the impact on the antenna performance due to multiple slots etched on the radiating surface of the antenna.

The evaluation is divided into two types :
1.) Slotted Microstrip Patch Antenna (SMPA) with Diode-ON/OFF
2.) Slotted Microstrip Patch Antenna (SMPA) array with Diode-ON/OFF

The BAP65-02,115 PIN diode is used to achieve frequency reconfigurability, the diode is simulated in the form of lumped RLC components. Table 1 shows the specification of the PIN diode used in the simulation i.e., Lumped RLC values for DON and DOFF. Figure 1 shows the equivalent circuit of the PIN diode for the ON and OFF states.

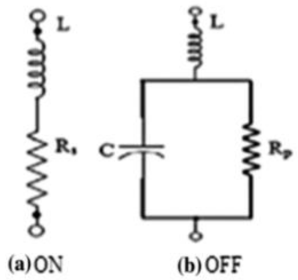


Figure 1: Equivalent circuit of BAP65-02,115 PIN diode for ON and OFF state

Table 1: BAP65-02,115 PIN diode Lumped RLC values.

Diode State	Resistance	Capacitance	Inductance
ON	1Ω	-	0.6nH
OFF	20KΩ	0.5pF	0.6nH

3. RESULTS AND DISCUSSION

The paper focuses on evaluating the impact of multi-slots etched on the radiating Rectangular Microstrip patch and to carry out parametric analysis to fix the dimensions and position of the slots until the expected results are achieved. The antenna parameters considered are Return Loss (S_{11}), Resonant Frequency (F_r), VSWR, and Gain.

The Summarized results of all four combinations of antennas are depicted in Table 2. High-Frequency Structure Simulator (HFSS) is used for the simulation of the proposed Microstrip parasitic patch antenna.

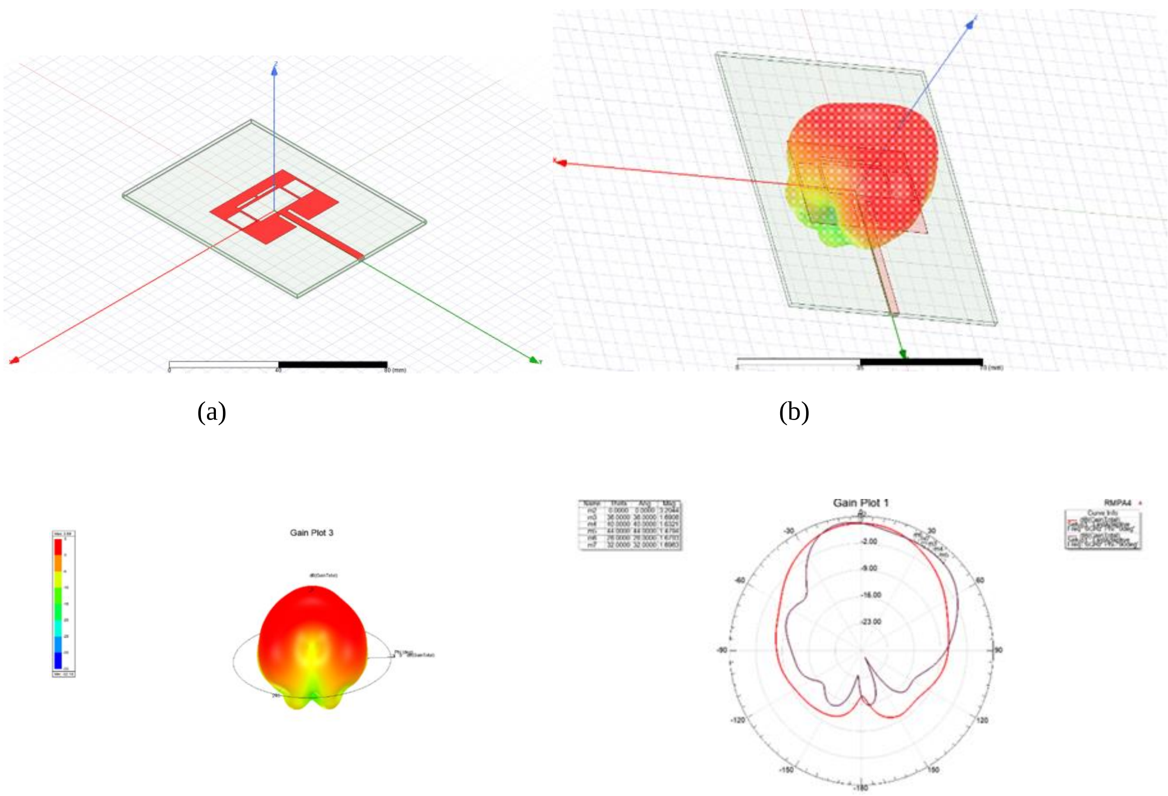
Table 2: Result summary for SMPA DON, SMPA DOFF, SMPA Array for DON, and SMPA array for DOFF

Design Stages	S_{11} (dB)	F_r (GHz)	VSWR	Gain (dB)
SMPA with DON	-25.37	3.76	1.11	3.59
	-12.42	4.93	1.6	
	-15.96	5.94	1.3	
	-33.08	6.12	1.04	
	-34.10	9.8	1.04	

SMPA with DOFF	-20.24	3.74	1.2	3.2
	-16.75	5.0	1.3	
	-31.46	9.7	1.05	
SMPA Array with DON	-27.48	3.76	1	6.63
	-12.44	4.93	1.6	
	-18.51	5.94	1.2	
	-36.68	6.12	1	
	-45.99	9.8	1	
SMPA Array with DOFF	-20.98	3.74	1.1	6
	-17.27	5	1.3	
	-29.63	9.75	1.06	

3.1 Slotted Microstrip Patch antenna with Diode ON/OFF

Three Slots were etched on the radiating element to analyze its impact, the addition of the resultant structures altered the current distribution making the structure have multiple resonances. The switching state of the diode (ON/OFF) provides the design more flexible. Figure 2. Depicts the geometry, radiation pattern, and Gain for the SMPA DON



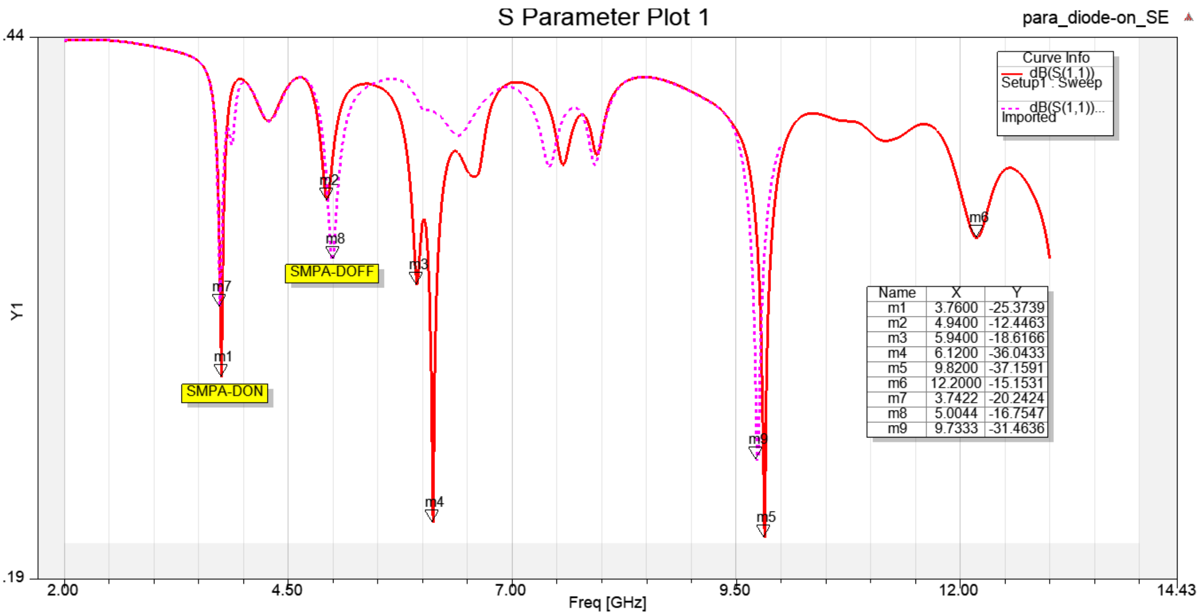
(a) (b) (c)

Figure 2: SMPA DON: (a) Geometry (b) Radiation Pattern and (c) Gain

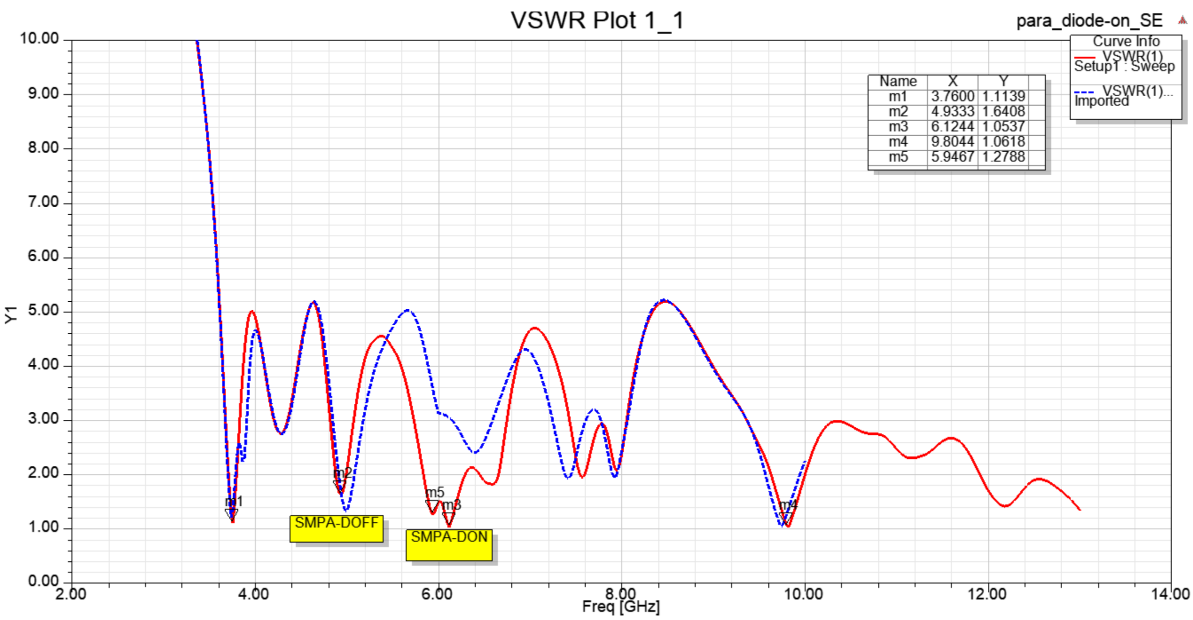
The directional radiation pattern with a Gain of 3.59 dB was observed. The Length (l), width (w), and position of the slots are based on the results obtained from Parametric analysis. Figure 3. Illustrates Return loss (S_{11}) and VSWR along with current distribution fields for

SMPA DON-DOFF. The below graph has a dashed line representing SMPA DOFF. The insertion of any geometrical shape on the radiating patch surface alters the electric field distribution which varies the capacitance and a change in the magnetic field alters the inductance. These changed values can be represented in terms of equivalent capacitance and inductance in the circuit.

The SMPA DOFF state enables a change in resonance frequency, due to the diode OFF state the electrical length of the antenna is changed, altering the current distribution along the radiation surface. The path length along which the current flows increase resulting in the resonant frequency shifting toward the lower end. The insertion of slots inserts additional current path changes as shown in the current distribution in Figure 3.



(a)



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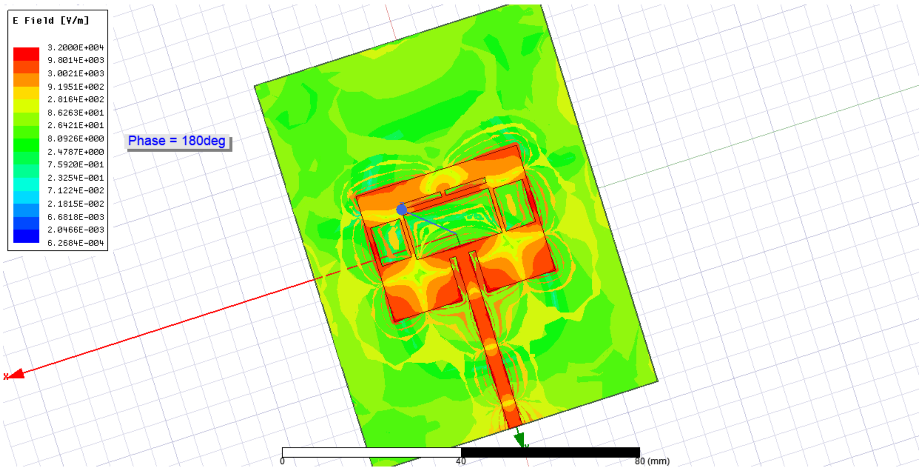


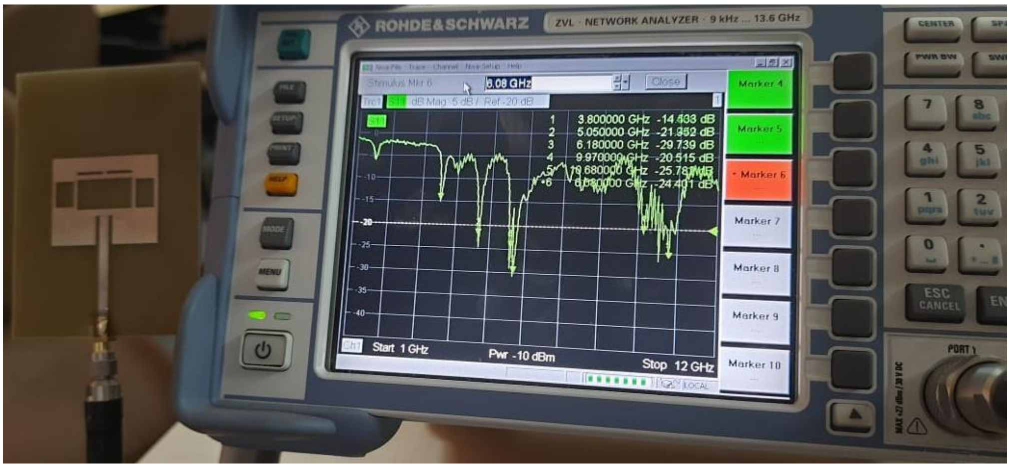
(c)

Figure 3 : (a) Return loss (S_{11}), (b) VSWR, and (c) Current Distribution SMPA DON-DOFF

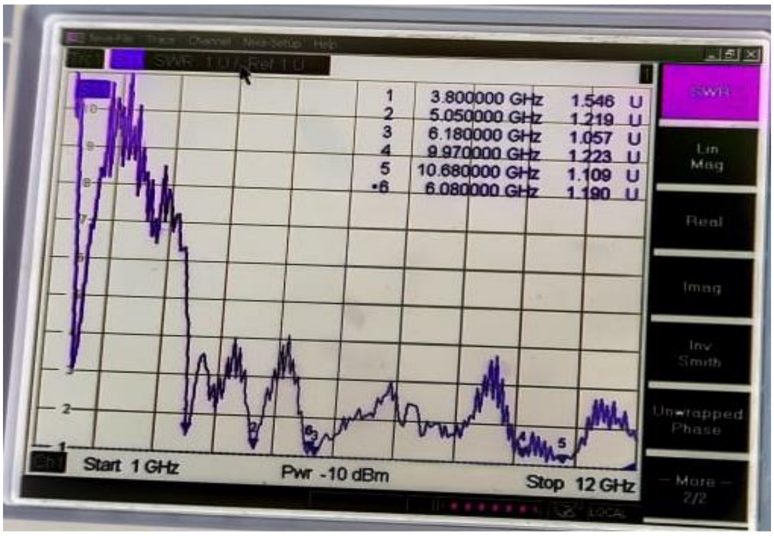
Comparison of simulated and measured results are depicted in Table 3 and Figure 4 demonstrates the hardware testing results for return loss and VSWR. The results obtained for simulated and measured show good agreement.

Table 3: Simulated and measured results for SMPA DON

SMPA DON (Simulated)			SMPA DON (Measured)		
f_r (GHz)	S_{11}	VSWR	f_r (GHz)	S_{11}	VSWR
3.76	-25.37	1.11	3.8	-14.57	1.52
4.933	-12.42	1.62	5.05	-21.952	1.21
5.946	-15.96	1.37	6	-24.401	1.1
6.12	-33.08	1.045	6.18	-29.739	1.05
9.8	-34.10	1.04	9.97	-20.515	1.22



(a)



(b)

Figure 4: Hardware testing results (a) Return loss (b) VSWR for SMPA DON

The comparison of simulated and fabricated measurements for SMPA DOFF shows a magnificent deal of accord. Table 4 depicts the comparison of the results and Figure 5.

Table 4: Simulated and measured results for SMPA DOFF

SMPA DOFF (Simulated)			SMPA DOFF (Measured)		
f_r (GHz)	S_{11}	VSWR	f_r (GHz)	S_{11}	VSWR
3.74	-20.24	1.2	3.8	-12.764	1.6
5	-16.75	1.3	5.13	-25.94	1
9.7	-31.46	1	9,97	-18.20	1.2

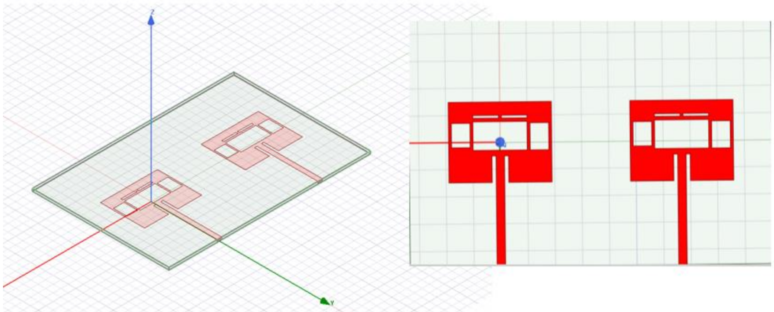
(a)

(b)

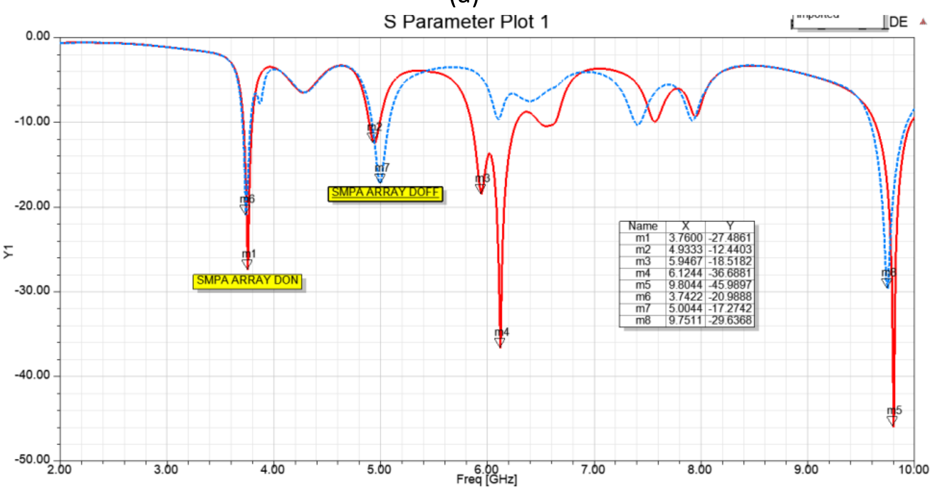
Figure 5: Hardware testing results (a) Hardware setup and S_{11} (Return loss) (b) VSWR for SMPA DOFF

3.3 Slotted Microstrip Patch Antenna (SMPA) array with Diode-ON/OFF (Two-element)

The single-element approach for both SMPA DON and DOFF was extended to multi-element configuration i.e. Array combination. Figure 6 explores this combination of antennae with results for Return loss, VSWR, impedance, Gain, and current distribution. Multi-element configuration of SMPA DON-DOFF demonstrates a fair degree of isolation between the two elements.



(a)



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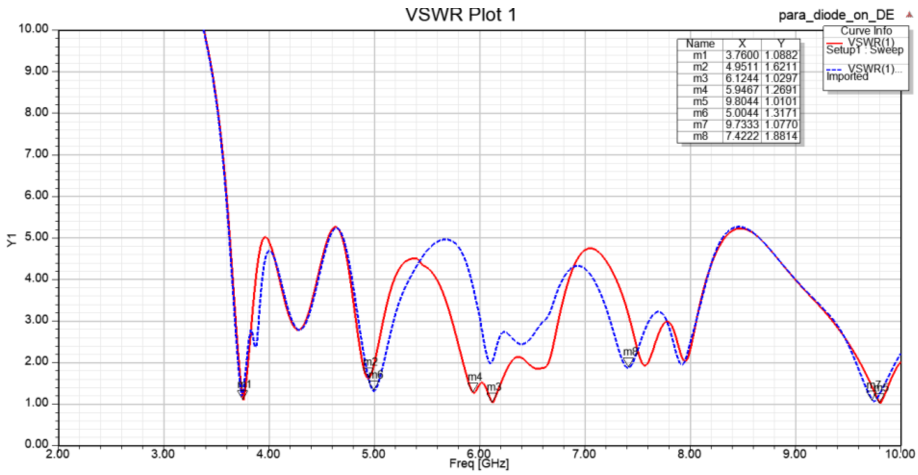

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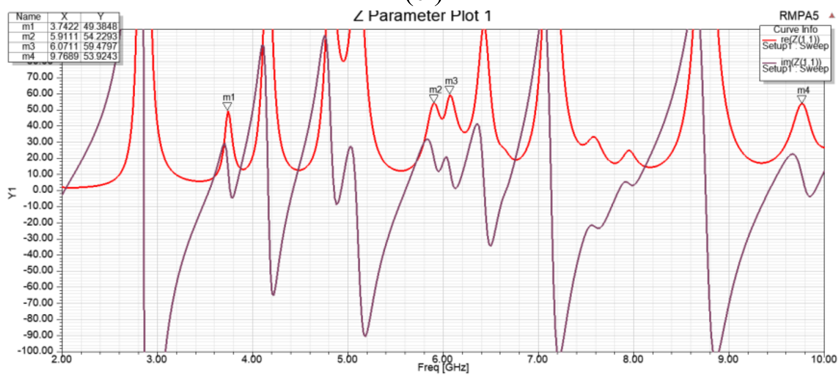

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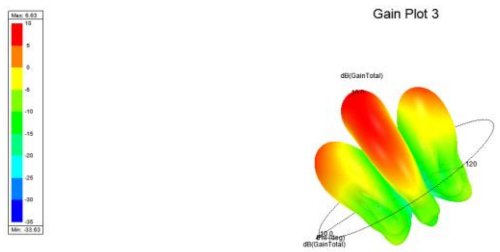
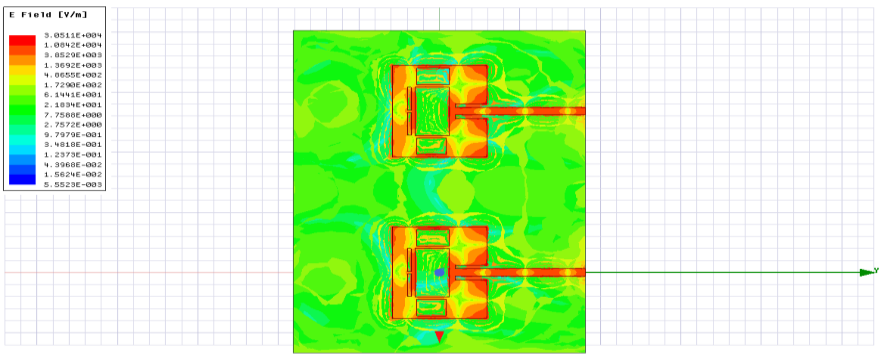


(e)



(f)

Figure 6: (a) Geometry (b) S_{11} (c)VSWR (d) Impedance (e) Gain (f) Current Distribution

The testing setup along with the measured results are depicted in Figure 7 and Table 5.

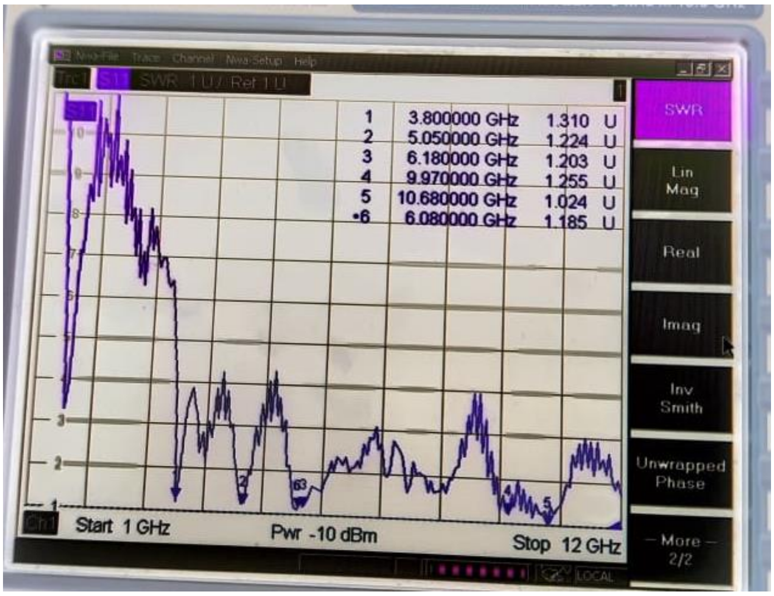


Figure 7: Hardware testing results (a) return loss (b) VSWR

Table 5: Simulated and measured results for SMPA Array DON (2-element)

SMPA Array DON (Simulated)			SMPA Array DON (Measured)		
f_r (GHz)	S_{11}	VSWR	f_r (GHz)	S_{11}	VSWR
3.766	-27.48	1.08	3.8	-18.791	1.3
4.933	-12.44	1.62	5.05	-19.218	1.2
5.946	-18.51	1.26	6.08	-22.75	1.185
6.12	-36.688	1.02	6.18	-23.997	1.2
9.8	-45.98	1.01	9.97	-20.638	1.2

The orientation of the feed was investigated along the linear and orthogonal directions. The present linear orientation demonstrated the expected results for SMPA array DOFF in Figure 9.

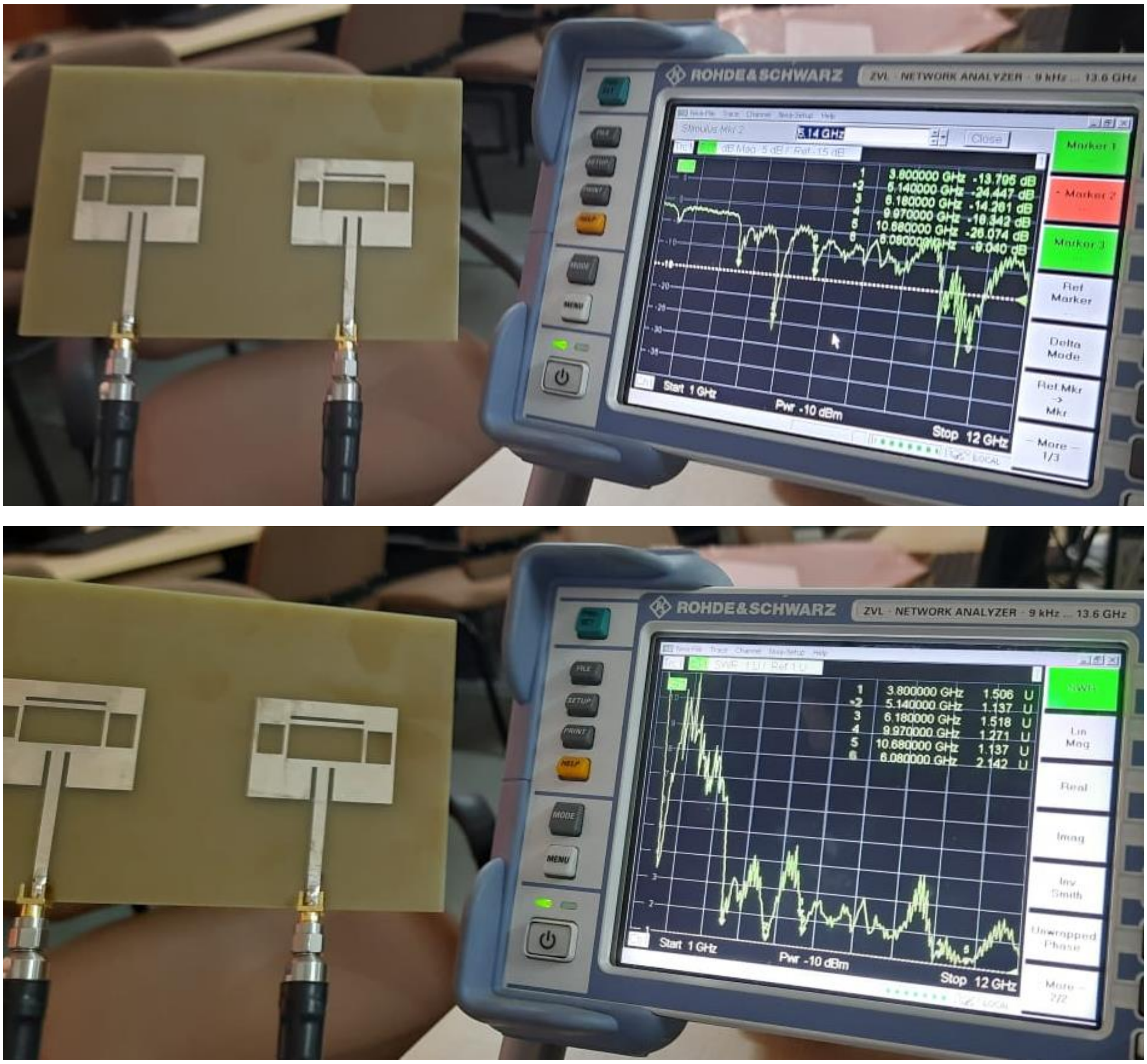


Figure 9: Hardware testing results (a) return loss (b) VSWR.

Table 6: Simulated and measured results for SMPA Array DOFF (2-element)

SMPA Array DOFF (Simulated)			SMPA Array DOFF (Measured)		
f_r (GHz)	S_{11}	VSWR	f_r (GHz)	S_{11}	VSWR
3.74	-20.98	1.1	3.8	-13.759	1.5
5	-17.27	1.31	5.14	-24.859	1.13
9.75	-29.63	1.06	9.97	-18.521	1.2

4. MATHEMATICAL MODELLING AND EQUIVALENT CIRCUIT

The equivalent circuit model in terms of lumped RLC circuit for the proposed Two element SMPA antenna array is depicted in Figure 10, which technically verifies the simulated results. The Proposed antenna is expressed in terms of its equivalent inductance and capacitance representing the geometrical changes implemented on the Microstrip antenna and simulated in an Advanced Design System (ADS) circuit.

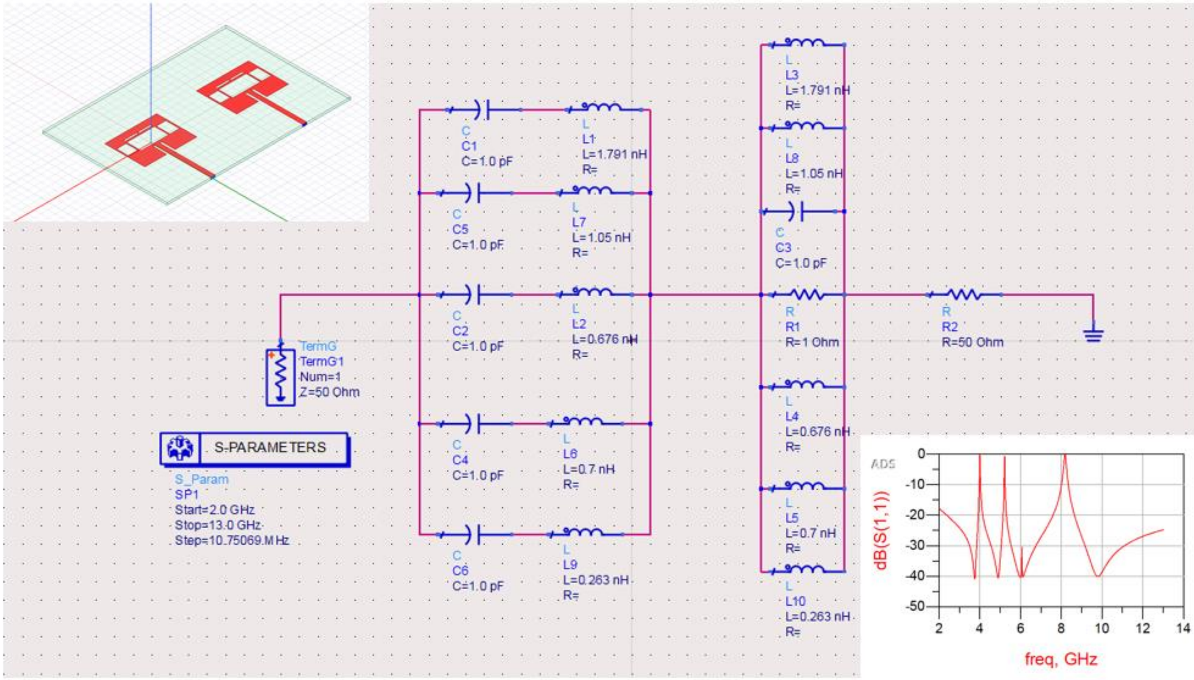


Figure 10: Equivalent Circuit for SMPA Array DON

As the current distribution is perturbed due to the slots etched on the radiating path, the path of the current is elongated. The length of the current path exhibits the series inductance whereas the etched gaps of the slots accumulate the charge, hence determine the series capacitance. The Resistance Value in RLC circuit represents the radiation resistance for the radiating mode at each resonant frequency.

The Lumped effect of the slots loaded on the radiating patch, which causes multiple resonance is represented as series combination of all the lumped elements with inductance represented as patch antenna and ground plane as capacitance load. The standard equations for antenna design from [13] were used beside using the following conventional equation for computing the individual resonance frequency for the given Multiband antenna shown in Equation 2 and Table 7 illustrates the values computed for R, L and C. Insertion of slot in the microstrip patch leads to change in length which is replicated by effective length L_e which considers impact of slot inserted with dimensions length L_s and width W_s.

$$F_r = \frac{c}{2L_e\sqrt{\varepsilon_{eff}}} \qquad (1)$$

Where, Le = Effective Length of the antenna and ϵ_{eff} = Effective Dielectric constant

$$F_r = \frac{1}{\sqrt{2\pi LC}} \qquad (2)$$

Assuming C= 1pF, the computed Values for L (nH) are:

Table 6: Equivalent values for L and C for SMPA

Design Stages	F_r (GHz)	VSWR	S_{11} (dB)	L(nH)
SMPA with DON	3.76	1.11	-25.37	1.791
	4.93	1.6	-12.42	1.05
	5.94	1.3	-15.96	0.7
	6.12	1.04	-33.08	0.676
	9.8	1.04	-34.10	0.263
SMPA with DOFF	3.74	1.2	-20.24	1.791
	5.0	1.3	-16.75	1.05
	9.7	1.05	-31.46	0.263
SMPA Array with DON	3.76	1	-27.48	1.791
	4.93	1.6	-12.44	1.05
	5.94	1.2	-18.51	0.7
	6.12	1	-36.68	0.676
	9.8	1	-45.99	0.263
SMPA Array with DOFF	3.74	1.1	-20.98	1.791
	5	1.3	-17.27	1.05
	9.75	1.06	-29.63	0.263

Moreover, the slots etched on the radiating surface along with the diode switching are modelled by six parallel LC network consisting of L1, L2, L3, L4, L5, L6 equivalent inductance and C1 to C6 Capacitors, the computed values for L and C are shown in Table 7.

Where R represents the radiation resistance, C represents the fringing effect at the radiating edges of the metallic patch and L accounts for the current detouring around the slots.

5. CONCLUSIONS

The results for the frequency reconfigurable antenna array demonstrate Multi-band frequency operations. The antenna is designed to operate at five frequencies 3.7 GHz/ 5 GHz/ 6 GHz /9.8 GHz with S11 < -10 dB and VSWR < 2. The communicating bands and the bandwidth achieved by the reconfigurable antenna are 3.72 - 3.8 GHz / 2.1% bandwidth, 4.89 – 5 GHz / 2.2% bandwidth, 5.85 – 6.28 GHz / 7.2% bandwidth, and 9.63 – 9.97 GHz / 3.4% bandwidth. The design holds great potential for future wireless applications which include Cognitive Radio, MIMO applications, Ad hoc Wireless sensor networks, IOT, and many more.

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