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Design and Implementation of Reconfigurable MIMO Antenna Based on Diodes for 5G Mid/High Frequencies

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Abstract

This paper presents a reconfigurable quad-element frequency-MIMO antenna designed to work at sub-6 GHz and 38 GHz of the fifth generation (5G) spectrum. The proposed design uses orthogonal radiating elements to provide more isolation (>15 dB) and pattern diversity. The antenna is fabricated on a Rogers RT/Duroid 5880 substrate with dimensions of $48 \times 48 \times 0.8\, mm^3$, a loss tangent of 0.0009, and a dielectric constant of 2.2. Switching between the far diverse bands of 5G communications using a MIMO reconfigurable antenna is a significant way of this work aims to perform. The RLC equivalent circuit's ON/OFF response determines two types of PIN diodes used that perform differently. Diodes used in mid/high-frequency 5G bands are evaluated to choose the best of the target frequencies. According to CST simulations, SMPPSC79 diodes function best at 5.15 GHz with (4.58-6.45) GHz bandwidth running, and MACOM MADP-000907-14020 diodes perform best at 38 GHz with (36.2-39.6) GHz operation bandwidth. High performance is obtained with a diversity gain of 9.8 and an envelope correlation coefficient of less than 0.04. Additionally, the Antenna peaks at a gain of 6.14dB and a total efficiency of 87% in the two frequency bands. These results suggest that the frequency-reconfigurable MIMO antenna is suitable for 5G applications.

Keywords: Compact quad-port antennas, Dual-Band, 5 G applications, High isolation, Reconfigurable antenna

1. Introduction

The demand for multi-band operation, higher data rates, enhanced channel capacity, and improved connection reliability is increasing in contemporary wireless communication systems [1],[2]. Multiple-input multiple-output (MIMO) antenna systems have been demonstrated to be a feasible solution for satisfying these requirements in numerous studies [3]-[5]. Reconfigurable frequency antenna systems are prioritized in order to mitigate system complexity [6],[7]. These systems can be reconfigured using a variety of technologies, including P-type Intrinsic (PIN) diodes [8],[9], Radio Frequency Micro-Electro-Mechanical Systems (RF MEMS) [10],[11], varactor diodes [12],[13], liquid metal [14], and field-effect transistors (FET) [15]. The PIN diode is particularly popular among these due to its compact size, low cost, and simplicity of integration. The literature has exhaustively investigated a variety of frequency reconfigurable antenna designs that employ PIN diodes. For instance, a frequency reconfigurable patch antenna that utilizes two PIN diodes (SMP1320-079) and includes ground plane positions can accommodate ten frequencies within the range of 2.2 GHz to 6 GHz [16]. Three PIN diodes (BAR65-03) are employed in an additional design that resonates at eight distinct frequencies [17]. An ACPW-fed frequency reconfigurable antenna operating in the Sub-6 GHz range is introduced in [18] in the context of 5G and Ultra-Wideband (UWB) applications. This antenna is equipped with a single PIN diode (BAR6402). Additionally, three PIN diodes (SMP1345-079LF) are employed to construct a four-mode antenna that encompasses nine frequency bands [19]. Other designs include compact reconfigurable antennas for 5G that operate at 28 and 38 GHz [20], mobile antennas that utilize defected ground structures and complementary split-ring resonators for wideband operations [21], and dual-band reconfigurable antennas that are controlled by frequency transitions using PIN diodes [22]-[24]. Numerous MIMO frequency reconfigurable antennas have been reported, in addition to single-element designs. A wideband reconfigurable antenna for sub-6 GHz applications is described in [25]. This antenna utilizes a varactor diode to alternate between two resonant bands. S, Ghanshyam et al. [26] discussed a four-element MIMO system that achieves eighteen modes by employing five PIN diodes per antenna for sensing and 4 PIN diodes per antenna for communication. Additionally, a two-element MIMO system with improved isolation, which operates in two modes (2.4 GHz and 3.5 GHz), is introduced in [27]. Other interesting designs include a 4×4 frequency reconfigurable MIMO system for WLAN applications [28], dual-band MIMO antennas that cover 2.5 to 3.6 GHz [29], and a quad-port MIMO architecture in which a single PIN diode is used to switch operation among the 2.5, 3.5, 5, and 5.7 GHz bands [30].

This paper introduces a compact MIMO antenna system that is specifically planned for operation within the 5G spectrum at sub-6 GHz and 38 GHz. Switching between diverse frequency channels is considered a valuable innovation of the system. Two varieties of PIN diodes are utilized to achieve optimal performance across both bands, as a single diode type is unable to support both frequency ranges efficiently. The MIMO system is comprised of four antennas that are integrated orthogonally on a single substrate using a self-isolation method. This results in a low envelope correlation coefficient and robust isolation (>15 dB) in both modes, which validate the system's diversity performance. The paper investigates the following antenna characteristics: efficiency, gain, envelope correlation coefficient (ECC), surface current distribution, reflection coefficient, and radiation patterns. The results verify that the proposed system satisfies the needs of emergent wireless communication technologies.

The contributions of this work are summarized as follows:

(i) A compact MIMO reconfigurable antenna is presented to gain access to sub-6 GHz and 38 GHz of the 5G spectrum. To the best of our knowledge, this antenna is considered new due to its capability to switch between the far-apart bands.

(ii) Two types of PIN diodes were used in this design due to the bands being far apart and the behavior of diode types needing to be fixed and working with the same efficiency at both frequencies.

(iii) Diodes used in mid/high-frequency 5G bands are compared and assessed to determine the best for target frequencies.

The following sections are organized as follows: Section 2 demonstrates the proposed antenna design. Section 3 provides the measured and simulation results, and Section 4 concludes this research design.

2. Antenna Design and Analysis

This section describes the step-by-step design process and the design features in depth. The designed antenna element and MIMO antenna structure and their impact on antenna properties were initially emphasized. The equivalent circuit of the antenna is also analyzed in this section.

2.1 Design-Single Element

Fig. 1 illustrates the geometry of the proposed reconfigurable antenna. A Rogers RT5880 substrate is used in the antenna design, which has a loss tangent of 0.0009, relative permittivity of 2.2, and thickness of 0.8 mm. Its dimensions are $30 \times 18\, mm^2$. Table 1 provides an extensive characterization of the antenna's dimensional specifications and overall structural configuration . In this design, three PIN diodes are integrated to facilitate the transition between 5 and 38 GHz. As illustrated in Fig. 2, the circuit model is formulated using RLC components and is tested under both ON and OFF operating states. A series RL circuit behaves in the PIN diode ON state, which is characterized by the inductor (L) and a low-value resistor (R_L), while the RLC circuit depicts the OFF state, with the capacitor (C) parallel to a high-value resistor (R_H). The suggested design model examines the behavior of several commonly used PIN diode types. Based on their operational frequencies, these diodes are divided into two groups: one group operates at 5.15GHz, while the other operates at 38 GHz. The diodes and their equivalent circuits are described in detail in Table 2.

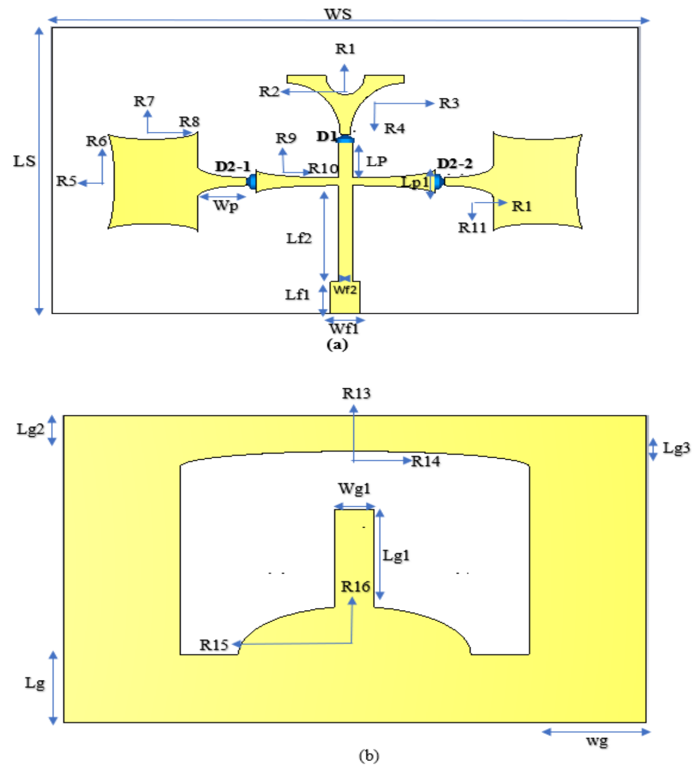


Figure 1. Suggested Reconfigurable Microstrip Antenna: (a) Front View, (b) Back View.

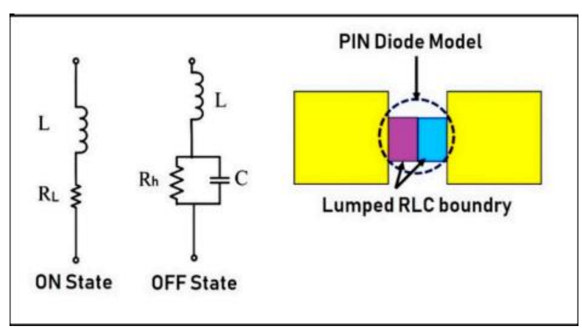


Figure 2. Biasing Circuits for PIN Diode.

Table 1. Dimensions of Proposed Reconfigurable Antenna

Par.	Ws	Ls	H	wf1	Lf1	wf2	Lf2	Lp
value (mm)	30	18	0.8	1.5	2	0.75	6	2.75
Par.	Lp1	wp	R1	R2	R3	R4	R5	R6
value (mm)	1.5	2.5	1.25	1	2.75	3.25	0.5	3.15
Par.	R7	R8	R9	R10	R11	R12	R13	R14
value (mm)	0.5	2.375	0.5	3.8	0.75	2.5	0.9	12
Par.	R15	R16	Lg	wg	Lg1	Wg1	Lg2	Lg3
value (mm)	6	2.8	4	6	5.74	1	2	1

Table 2. Commonly used PIN diode types.

No	PIN diodes in 5GHz	R_{ON} (Ω)	L	C	PIN diodes in 38GHz	R_{ON} (Ω)	L	C
1	HPND-4005	1	1.5nH	0.5PF	MA4AGBL912	4.9	0.5nH	30fF
2	BAR 6402	2.1	0.6nH	0.09PF	MA4AGFCP910	4.2	0.5nH	20fF
3	SMP 1320-079	0.9	0.7nH	0.3PF	MACOM MADP-000907-14020	7.8	30PH	28fF
4	SMP 1345-079LF	1.5	0.7nH	0.15PF	MA4FCP300	2.6	0.6nH	0.04 PF
5	SMPPSC79	1	0.6nH	0.3PF	SMP-1345(SC-79)	4.7	0.15 nH	0.017PF

The suggested design basically depends on the integration of two wide- slot square microstrip patch antennas, each configured to resonate at the specified frequencies at 5.15 GHz and 38 GHz, which is derived from equations (1) to (5) [19]. These antennas are merged with a lot of modification and optimization to get to the ultimate design of Fig. 1

The width (W) of the substrate is given as

$$W = \frac{c}{2f_o}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

f_o *is resonant frequency*
third Where ε_r is the dielectric substrate's relative permittivity (F/m), and c is the light speed 3×10^8 m/s

According to the height (h), the effective dielectric constant is given as:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{w}\right)^{\frac{-1}{2}} \quad (2)$$

The effective length is calculated as:

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} \quad (3)$$

where f_o is the resonance frequency (Hz)

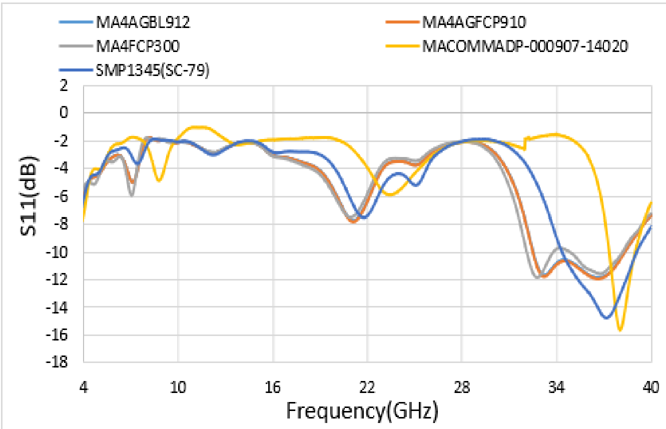
The extension length ΔL is given as:

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8)} \quad (4)$$

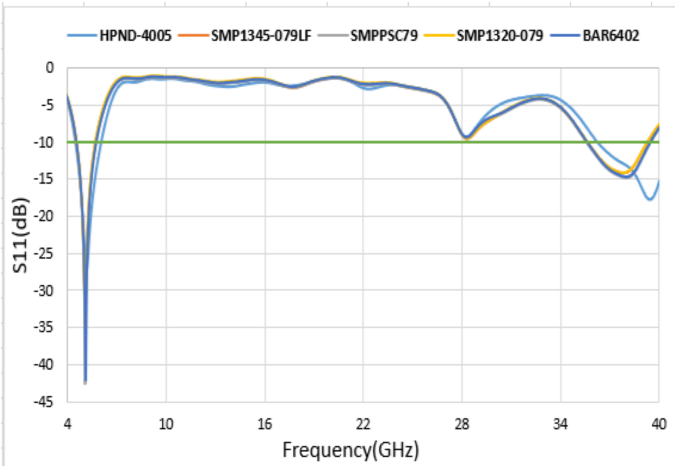
The actual length of the patch antenna is given as:

$$L = L_{eff} - 2\Delta L \quad (5)$$

Under two operational modes, the antenna is evaluated and compared using various diode configurations to determine which type of diode yields the best favorable response at the objective frequency. When D_{2-1} &D_{2-2} are deactivated and D_1 is enabled, the proposed antenna operates in case 1, resonating at 38 GHz. The diodes' responses are compared, where the results of S11 are shown below -10 dB. Results indicate that the PIN diode type (MACOM MADP-000907-14020) provides the most favorable response performance among the proposed diode types, achieving S11(-33.5), as illustrated in Fig. 3(a). Case 2, when D_{2-1} and D_{2-2} =enable, whereas D_1= disabled, the proposed antenna starts operating at the frequency band 5.15 GHz. When testing the responses of various types of diodes, the PIN diode (SMPPSC79) shows a superior response relative to others, as evidenced by the simulation results yielding S11=-42.32 d as shown in Fig. 3(b).

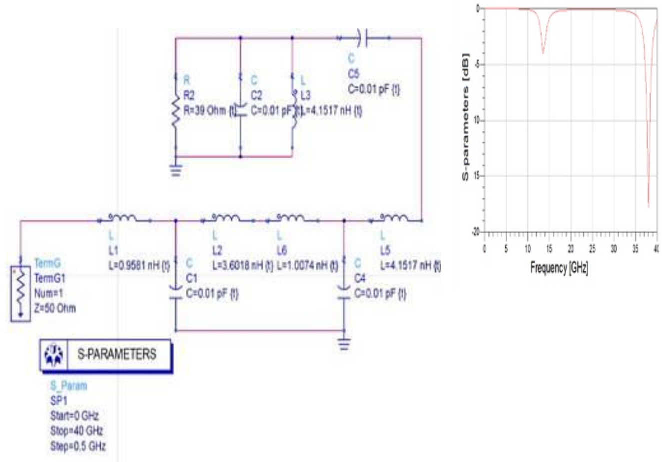


(a)

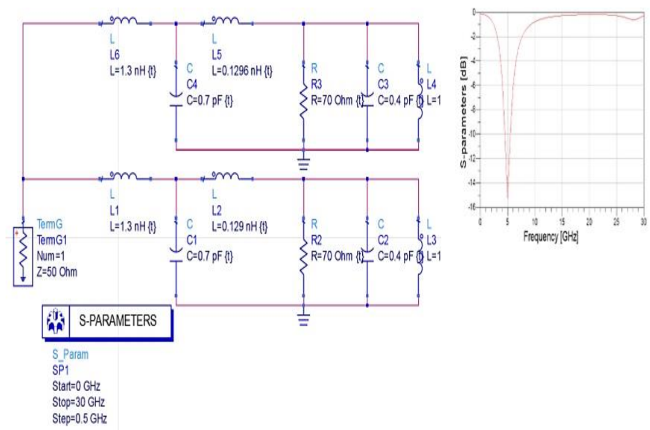


(b)

Figure3. Simulated Return Loss at (a) 38GHz and (b) 5.15GHz.



(a)



(b)

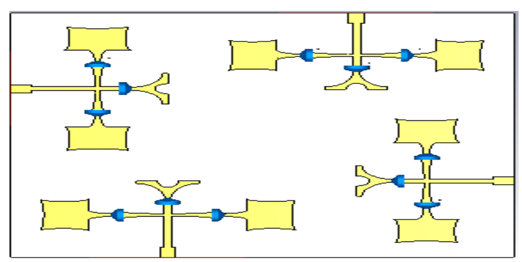
Figure 4. Equivalent circuits: (a) Mode 1 (b) Mode 2

2.2 Circuit Analysis

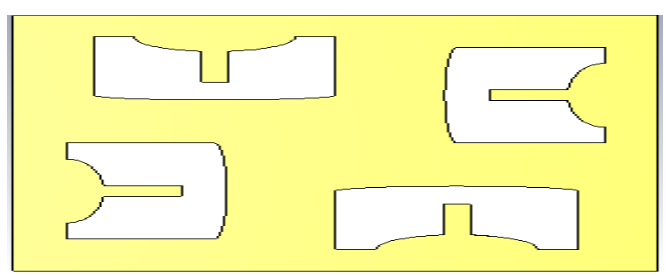
The suggested antenna equivalent circuits of the two operating modes are explained in this section. The software package Advanced Design System 2019 (ADS 2019) is used to evaluate the design of these circuits at dual-mode operation. Fig. 4 (a) and (b) present the RLC circuit of a 50 Ohm input-line- fed antenna in two modes that are related to the input reflection coefficient curves. For validation, the S11 response obtained from the RLC circuit model for both cases using ADS is nearly identical to the results from the CST simulator, which proves operation in the desired bands.

2.3. Four-element antenna design

A four-element MIMO antenna array was designed based on the proposed single antenna configuration, as illustrated in Fig. 5. The MIMO antenna array has an overall dimension of 48 × 48 × 0.8 mm³. To achieve reconfigurability, 3 PIN diodes are integrated into the radiating elements of each antenna. The 4 MIMO antenna elements are placed perpendicularly in the same substrate to improve isolation, so the necessity for decoupling is eliminated.



(a)



(b)

Figure 5. Geometry of Proposed Four-Element MIMO Antenna: (a) Front and (b) Back View.

3. **Results and Discussion**

Fig. 6 illustrates the simulated S-parameters for both operating modes. The antenna operates at a frequency of 38 GHz when diode D1 is activated only, whereas when diode D2 is activated only, it resonates at a frequency of 5.15 GHz. The simulated isolation outcomes of the MIMO antenna for all modes are depicted in Fig. 7. As illustrated in Fig. 7, the S-parameters S12, S13, and S14 all exhibit values exceeding -15 dB as a result of the considerable mutual coupling between the radiating elements. Fig. 8 further demonstrates this mutual coupling by displaying the surface current distribution at 38 GHz and 5.1 GHz. The surface current traverses through the ground plane to the other antenna components when port 1 is excited, thereby enhancing its connection, even when only the first antenna element is activated. The ground planes of the antenna elements were not interconnected in previous studies, which resulted in a break in surface current flow between components. This enhanced isolation and reduced the necessity for decoupling networks.

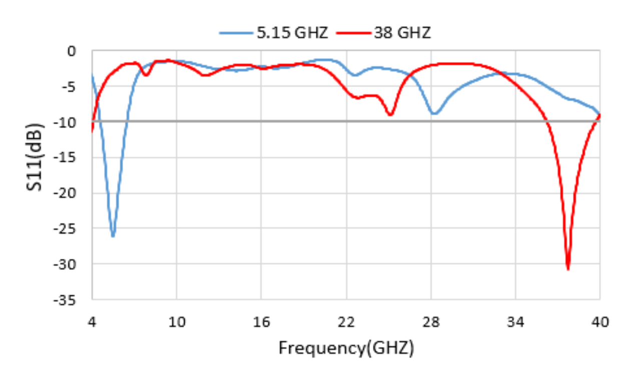
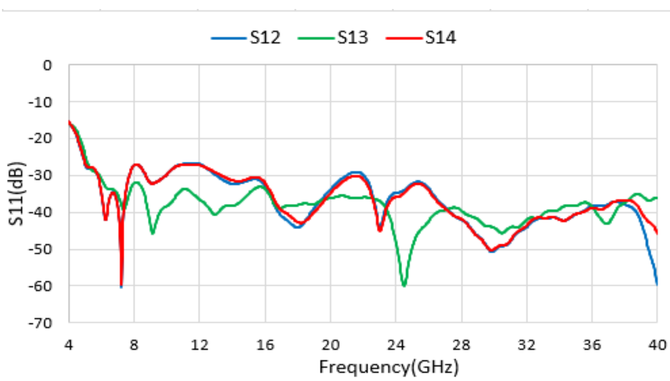
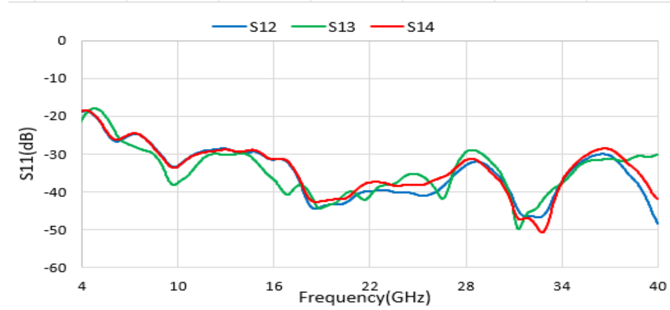


Figure 6. Reflection Coefficients of the proposed Antenna at 38 GHz and 5.1 GHz.

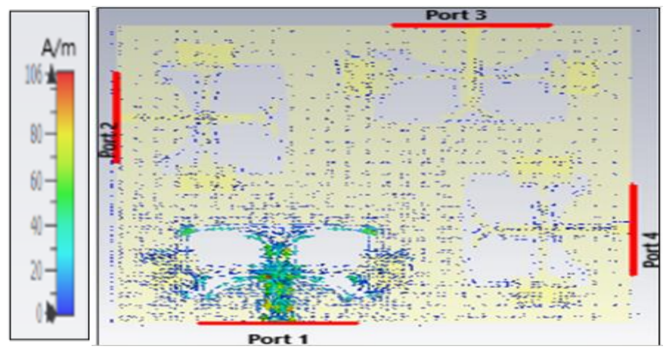


(a)

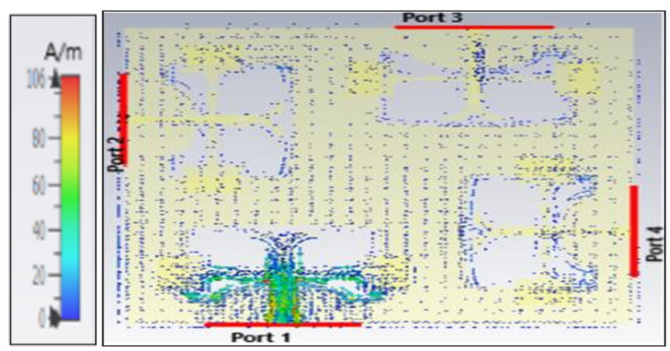


(b)

Figure 7. Simulated Coefficient Results of the proposed Antenna for (a) 38 GHz, and (b) 5.1 GHz.



(a)

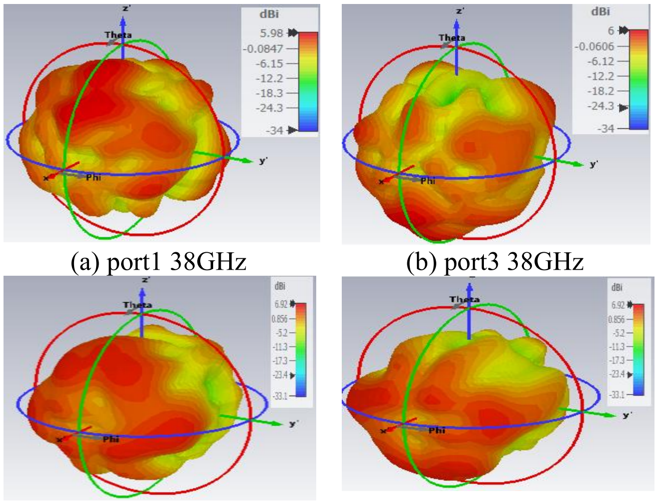


(b)

Figure 8. Surface Current Distributions with Port1 excited at (a) 38 GHz and (b) 5.15 GHz

Fig. 9 shows the quad-element MIMO antenna's 3D radiation pattern of different resonant frequencies in a semi-omnidirectional pattern.

The gain of the proposed MIMO antenna is illustrated in Fig. 10 in two different situations. The antenna gain is at its highest at 6.14 dBi at 5.15 GHz, with a range of 5.81 dBi to 6.14 dBi. Moreover, Fig. 11 shows that the overall efficiency of the antenna is close to 87% throughout the operating range, and it also provides better performance within the specified frequency bands.



(a) port1 38GHz (b) port3 38GHz

(c) port1 5.15 GHz *(d) port3 5.15 GHz*

Figure 9. The three-dimensional radiation pattern of the MIMO antennas for dual-ports at two frequencies, 38 GHz and 5.15 GHz.

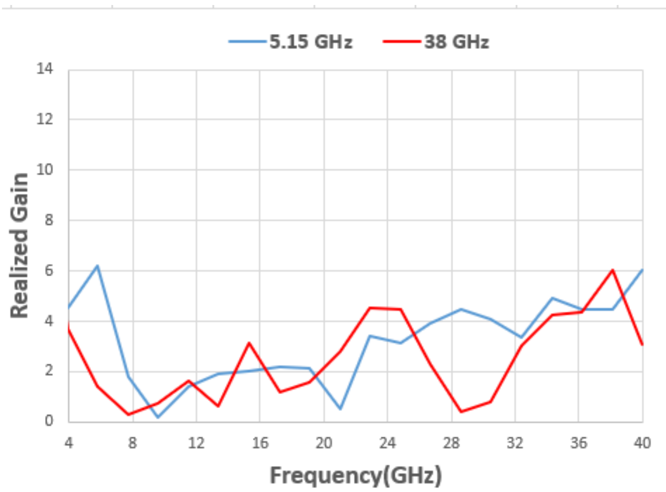


Figure 10. Realized Gain of antennas for all frequencies

Fig.12 depicts the fabricated prototype antenna's upper and lower planes, and Fig. 13 shows the Vector Network Analyzer (VNA KC901V) that was used to validate the antenna performance.

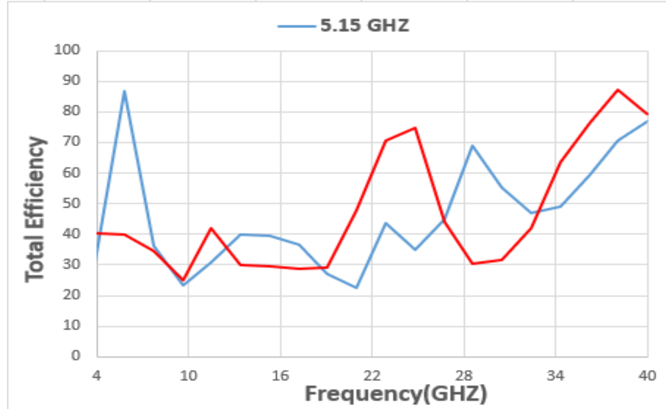
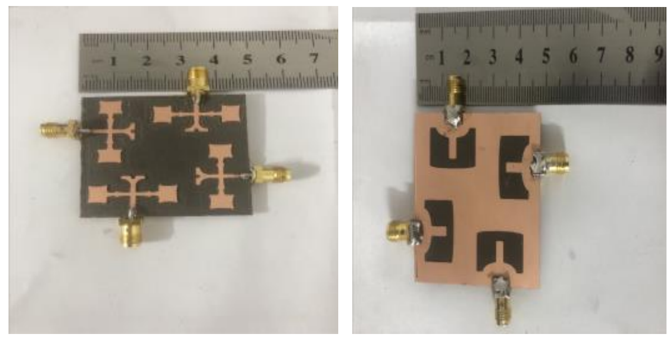


Figure 11. Total efficiency of the Antennas for all Modes.



(a)Top view (b) Bottom view

Figure 12. Fabricated Antenna

The |S11| measurements of sub-6 GHz compared to the simulation are shown in Fig.14. It is shown that there is a small variation in the measurement line curve compared to the simulation curve. This minor deviation is probably caused by the antenna fabrication process, the feeding port, and antenna soldering. Fig. 15 illustrates the Mode 2 measured isolation results of the proposed antenna. It depicts a strong correlation between the measured and simulated isolation results.

Figure 13. VNA Analyzer used to measure the S-parameters.

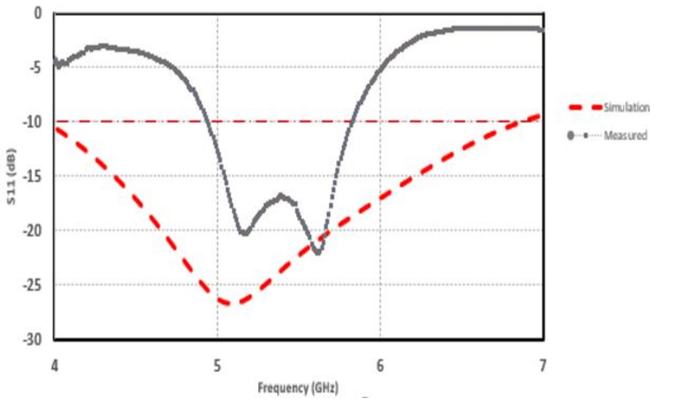


Figure14: Mode 2 simulated measurement of the reflection coeffic

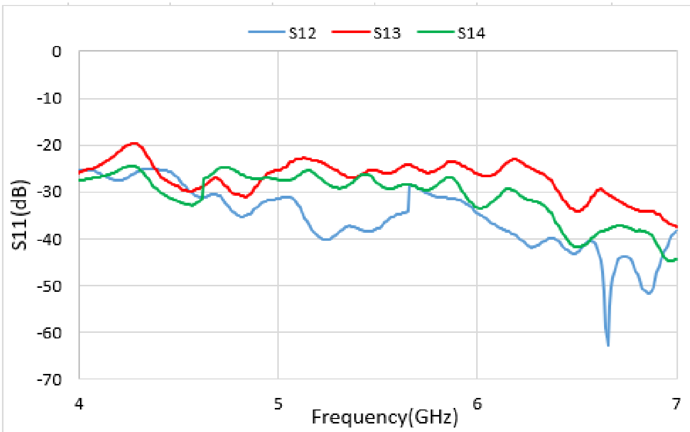


Figure 15. Mode 2 proposed antenna measured transmission coefficient

3. Performance of the Proposed MIMO Antennas

The MIMO performance of the proposed antenna with reconfigurable components is confirmed by critical essential performance metrics, such as the ECC and DG. The ECC of the MIMO antenna that has been designed is determined by utilizing Eq. 6 to analyze a far-field radiation pattern [31], [32]. Fig. 16 illustrates that, for optimal MIMO performance, the allowable ECC value is typically less than 0.5, and the ECC for the two resonance modes is below the 0.04 level. The proposed MIMO system is highly appropriate for delivering diversity performance in the intended frequency bands.

$$\mathrm{ECC} = \frac{|S_{ii}^{*}S_{ij}+S_{jj}^{*}S_{ji}|^2}{[1-(|S_{ii}|^2)+|S_{ij}|^2][1-(|S_{jj}|^2)+|S_{ji}|^2]} \tag{6}$$

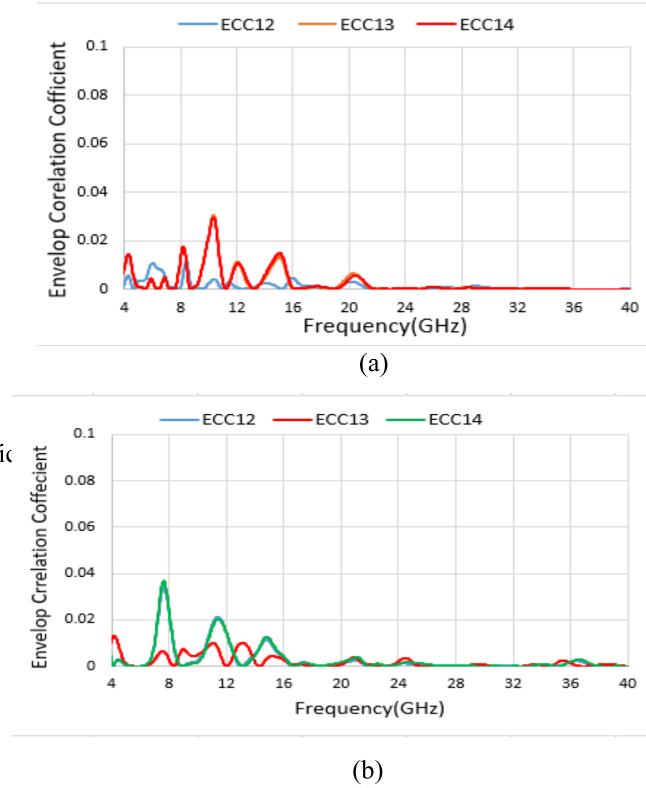


Figure 16. ECC of dual frequency: (a) 38 GHz (b) 5.15 GHz

In addition to this, the diversity gain is related to ECC [31[, [32] via a mathematical formula.

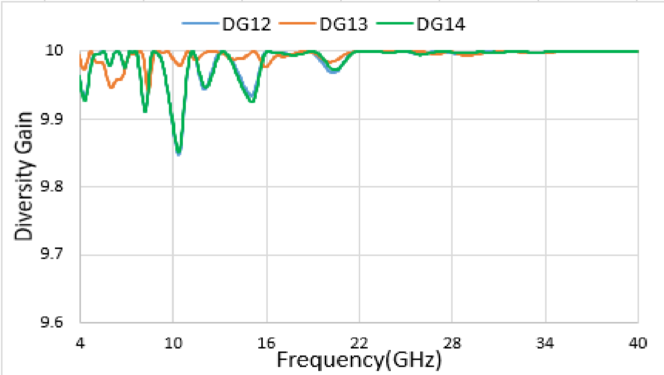
$$\mathrm{DG} = 10\sqrt{1-(\mathrm{ECC})^2} \tag{7}$$

Fig. 17 illustrates the diversity gain (DG) of the proposed MIMO antenna in both operating modes. The MIMO antenna system exhibits better diversity performance, as evidenced by the DG of more than 9.8 dB in both modes.

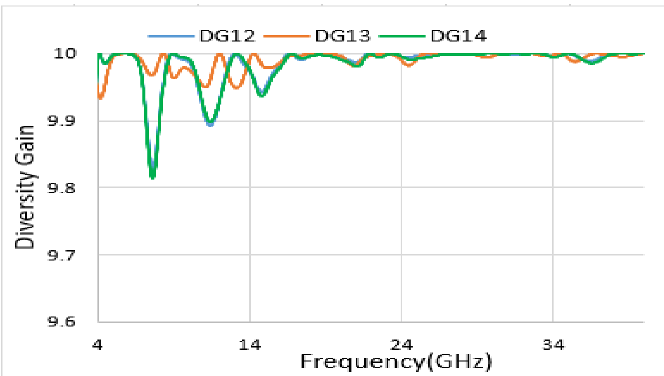
Table 3 illustrates the comparison between this work and previously reported MIMO antennas. It is evident that the design is novel, as no prior research has been conducted in the same MIMO configuration between the sub-6GHz and MM-Wave bands. The design has also been demonstrated to have high isolation and a decent calculated total efficiency, resulting in low ECC results among all the reported MIMO antennas. This suggests that it is more suitable for 5G applications.

Table 3. Comparison with previous work MIMO Antenna

Ref.	Size mm^2	Operation bands	MIMO Elements	Isolation dB	ECC	DG (dB)
[26]	50x38	WiMax, Cband, WLAN, Xband	4	-15	<0.15	9.5
[27]	120x60	(2.4&3.5) GHz	2	-12	<0.005	<10
[29]	60x100	(2.5–3.6) GHz	2	-15	<0.16	NM
[30]	50x50	(3.5&5.7) GHz	4	-13	< 0.5	9.95
Prop. work	48x48	(5.1&38) GHz	4	>-15	<0.04	>9.8



(a)



(b)

Figure 17. The DG; (a) 3.8 GHz, (b) 5.15 GHz

4. Conclusion

This paper proposes a compact frequency reconfigurable MIMO antenna targeted at the sub-6 GHz and 38 GHz regions of the 5G spectrum. This design is reconfigurable via two groups of switches that connect/disconnect specific antenna sections that decide the mode of operation. The suggested antenna operates in two modes that depend on the switches' ON/ OFF states. In mode 1, the antenna operates at 38GHZ when D1 is entirely ON, while in mode 2, the antenna operates at 5.15GHZ when only the group of D2 is ON. The proposed design represents a novel improvement over prior configurations by enabling a transition between frequency regions that are widely separated. Specifically, four orthogonally arranged elements on the Rorer RT5880 substrate are employed to achieve a mutual coupling between the elements exceeding 15 dB. The MIMO antenna that has been proposed has an ECC of less than 0.04, a high DG> 9.8, a good gain, and an efficiency of over 87%. The results indicate that a quad-port MIMO antenna is a suitable candidate for use in 5G applications. Investigating antenna miniaturization methodologies that preserve or enhance efficiency and overall performance represents a promising direction for future research.

Conflicts of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Zainab H. Makath. and Asaad S. Daghal developed the primary concepts and the proof outline.

Qasim Hadi Kareem analyzed the experimental data and manufactured the prototype. All authors contributed to the interpretation of the results and to the manuscript.

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