Journal of Nano- and Electronic Physics
Vol. **18** No 4, 04025(8pp) (2026)

Журнал нано- та електронної фізики
Том **18** № 4, 04025(8cc) (2026)

REGULAR ARTICLE

Design of a Miniaturized Frequency-Reconfigurable Microstrip Antenna Using PIN Diodes and Defected Ground Structure for Modern Wireless Communication

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(Received 10 March 2026; revised manuscript received 17 August 2026; published online 21 August 2026)

This paper presents a frequency-reconfigurable microstrip patch antenna with a modified defect in the ground plane. Frequency reconfiguration is achieved using two PIN diodes embedded in the ground plane at the appropriate locations. A DC biasing network was incorporated to supply the PIN diodes. The effect of the DC biasing network on the performance of the resonance frequency of the antenna is also presented. By altering the states of the PIN diodes, the antenna can operate in three different modes with resonance in four different frequency bands at 2.42 GHz (Wi-Fi), 3.62 GHz (n-78), 5.55 GHz (5G Wi-Fi), and 6.2 GHz (n-96). The proposed antenna has a small size of 16 × 17 mm² and is fabricated on a low-cost FR-4 substrate. A strong correlation between the simulation and measurement results of the reflection coefficient with $|S_{11}| \leq -10$ dB was achieved across all three operating modes of the proposed design, confirming its validity. The miniature size of the antenna makes it useful for modern wireless equipment, where space is the main issue.

Keywords: Miniature, DGS, Patch antenna, Frequency reconfiguration, PIN diode.

DOI: 10.21272/jnep.18(4).04025 PACS number: 84.40.Ba

1. INTRODUCTION

With the path-breaking growth in the wireless communication industry, there has been a growing concern for miniaturized wireless equipment that can support various wireless services. Reconfigurable antennas can provide various wireless services while remaining compact. These reconfigurable antennas are classified based on the antenna parameters that are affected, such as frequency, radiation pattern, polarization, or a combination of these. The reconfiguration is realized by altering the surface current distribution of the antenna using either mechanical or electrical radio frequency switches. Electrical switches in the form of PIN diodes, varactor diodes, field-effect transistors (FET), and microelectromechanical systems (MEMS) are used extensively to achieve reconfigurability [1-2].

For wireless communication systems, the designed antenna is compact and can cover multiple wireless services [3]. A frequency-reconfigurable antenna that serves the same purpose as separate antennas for each frequency band is an ideal solution, as it helps save space and cost.

Two approaches were used for antenna miniaturization. In the first approach, the substrate material properties are altered, resulting in a decrease in the effective wavelength in the substrate regions. In the second approach, the antenna geometry is modified to extend the path for the surface current, resulting in a frequency variation [4]. With the Defected Ground Structure (DGS) technique, the geometry of the antenna structure can be modified, and compact microstrip antennas can be achieved. DGS refers to a single or multiple slot embedded in the ground plane. These slots can have different geometrical shapes to alter the distribution of the surface current on the ground plane, resulting in the formation of additional resonators within the main structure [5]. To achieve antenna miniaturization, many researchers have used the concept of DGS [6-9].

To reconfigure the frequency of a circular patch antenna, an arc-shaped ground slot was proposed [1]. The arc-shaped slot length is controlled by using five PIN diodes, resulting in six frequency bands. A multiband reconfigurable hexagon-shaped radiating patch antenna with two inclined strips connected to the patch using PIN diodes for satellite TV, WLAN, and radar applications was reported [3]. A hexagonal patch frequency reconfigurable antenna with DGS is presented for antenna miniaturization in Internet of IOT applications. The antenna uses a varactor diode embedded in a microstrip feedline and has a size of 40 × 40 × 1.5 mm³ [8]. A miniaturized microstrip slot antenna for frequency reconfiguration using three PIN diodes was introduced [9]. The antenna is compact and measures 20 × 20 mm². A frequency reconfigurable Tri-Band antenna having compact size of 30 × 30 mm² for LTE/Wi-Fi/ITS applications is presented. To achieve frequency reconfigurability, two PIN diodes are placed in a rectangular bottom slot with a DC biasing circuit on top of the antenna [10]. A

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Cite this article as: D.O. Sakle et al., *J. Nano- Electron. Phys.* 18 No 4, 04025 (2026) https://doi.org/10.21272/jnep.18(4).04025

frequency reconfigurable antenna with asymmetric armed U and reversed L slots reported in [11] uses three PIN diodes and operates in six modes with resonance at 4.33, 4.63, 5.24, 5.87, 5.96, and 6.29 GHz. A reconfigurable antenna suitable for ISM, 5G Sub-6 GHz, and S-band applications was reported [12]. Utilizing two PIN diodes, it operates in single wideband, dual band, and tri band modes. A compact reconfigurable monopole antenna was presented [13], capable of operating in wideband (4-7.8 GHz), dual-band (3.3-4.2 and 5.8-7.2 GHz), and single-band (3.3-4.2 GHz) modes. These different operating modes are realized by adjusting the switching states of the two PIN diodes. An N-shaped frequency-reconfigurable antenna operating in four modes by incorporating two PIN diodes whose switching is controlled automatically using an Arduino board was presented [14]. A frequency-reconfigurable antenna incorporating two PIN diodes controlled using an Arduino Uno was presented [15]. This antenna is equipped with ring resonators as elements for frequency control as part of its structure. A compact antenna with frequency reconfiguration for wireless applications, having a defected ground plane and two PIN diodes operating in four dual-band modes, was reported [16]. A defected ground structure frequency-reconfigurable UWB antenna with single [17] and dual [18] band-notched functions is presented. A compact defected ground structure frequency-reconfigurable antenna with two PIN diodes for connecting an embedded split-ring resonator was presented for LTE and WLAN/WiMAX Wireless Systems [19]. In [20], for mid-5G and high-5G bands, a reconfigurable antenna with three PIN diodes operating in eight distinct modes was presented. A key-shaped frequency-reconfigurable antenna was proposed for LTE applications [21]. Reconfiguration is achieved using two PIN diodes, enabling four modes of operation: three single-band modes and one dual-band mode.

Meandered radiating patches, a partial ground plane, and a ground plane stub were used to achieve a compact design and impedance matching [22]. By utilizing three PIN diodes, the antenna operates at three primary frequencies for LoRa: 915, 868, and 433 MHz. A circular G-slot antenna with a circular DGS and three PIN diodes, one on the patch and the other two embedded into the DGS, was introduced [23]. The different antenna parameters were examined using ANSYS software.

A frequency-reconfigurable CPW-fed monopole antenna was described for IoT applications, featuring a 0.13 mm ROGERS 3003 flexible substrate [24]. The antenna measures 30×30 mm^2 and operates in three different frequency bands using two PIN diodes. The antenna gain is enhanced by positioning the FSS surface underneath it. A compact and flexible CPW-fed patch antenna in the form of a circular shape was introduced [25], featuring an RT5880 flexible substrate with a thickness of 0.254 mm for heterogeneous applications. The antenna incorporates two PIN diodes positioned in two different slots on the circular radiator, resulting in multi-mode and multi-band behavior.

As the size of wireless communication equipment is reducing day by day, antenna size is the prime concern for designing equipment for wireless applications. As the proposed antenna is miniature in size, it can help solve the problem of space limitations. The literature reviewed in this paper is based on the use of RF switching elements for achieving reconfigurability. In the available literature, the antenna size is considerable, which needs to be rectified. In addition, some studies propose various operating modes of the switches by turning them ON and OFF; however, they do not create isolated regions for the separation of positive and negative DC supplies, which is the main requirement for biasing the switches separately so that they can operate in a particular mode.

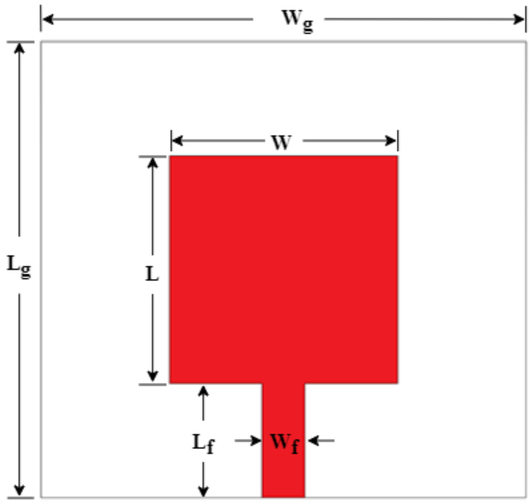
This study proposes a miniaturized patch antenna embedded with a defected ground structure, where two PIN diodes are used for switching. The ground plane defect affects the antenna surface current distribution, and the antenna can radiate at lower frequencies. Frequency reconfiguration is achieved by controlling the operating modes of the PIN diodes. A biasing network was provided on the antenna structure for the proper biasing of the PIN diodes. By creating three 0.25 mm slots with capacitors at appropriate locations, isolated regions were created such that the two PIN diodes could be biased independently.

2. ANTENNA DESIGN AND CONFIGURATION

2.1 Antenna Geometry

Fig.1 shows the design prototype of the antenna. The antenna is miniature and simple in construction, making it a good candidate for wireless equipment where available space is limited. For the antenna design, a low-cost FR-4 dielectric substrate (0.8 mm thick) with standard 0.035 mm thick copper cladding was used. For feeding the square patch, a microstrip feed line is used, as shown in Fig. 1a. As shown in Fig. 1b, the antenna ground plane is modified by introducing a novel defect, which helps to miniaturize the antenna.

Two PIN diodes, SW1 and SW2, are used on the ground plane for switching. The ON-OFF states of these switches were controlled separately so that the antenna could radiate at four different frequency bands. For modelling, analyzing, and optimizing various antenna parameters, the CST Microwave Studio is used. The antenna design parameters are listed in Table 1.



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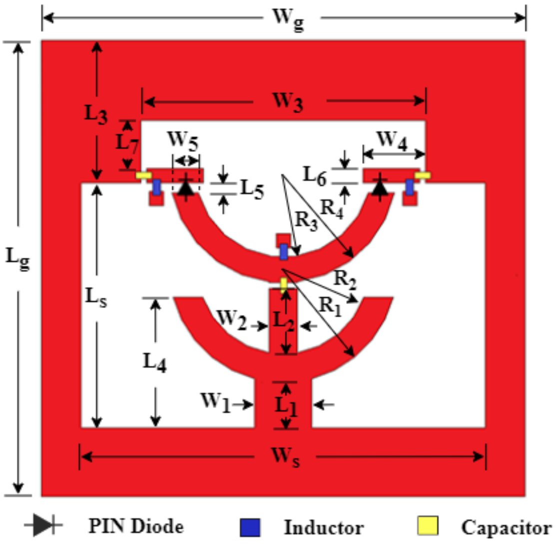


b

Fig. 1 – Antenna structure: front (a), back (b)

Table 1 – Antenna geometrical parameters

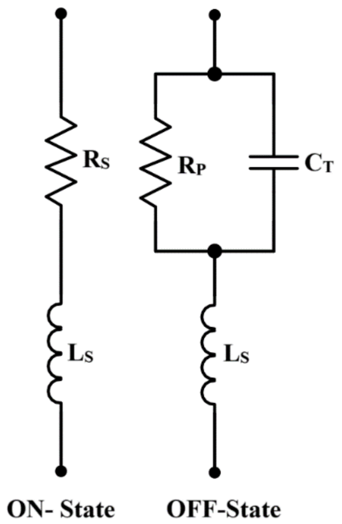
Parameter	Value	Parameter	Value
L	8	L_6	0.5
W	8	L_7	1.7
L_g	16	W_f	1.5
W_g	17	W_1	2
L_f	4	W_2	1
L_s	8.6	W_3	10
W_s	14.2	W_4	2.2
L_1	1.6	W_5	1
L_2	2.5	R_1	4
L_3	5	R_2	3
L_4	4.6	R_3	3
L_5	0.35	R_4	4

2.2 Switch Design and Biasing Network

Because the proposed antenna uses two PIN diodes for switching, there are four possible states of operation. In the proposed work, only unique modes of operation are considered. In mode-1, switch SW1 and SW2 are ON; in mode-2, switch SW1 and SW2 are OFF; and in mode-3, switch SW1 is OFF and switch SW2 is ON.

Fig. 2a shows the PIN diode lumped equivalent model in the ON-state and OFF-state. To provide high isolation during the OFF-state state, it is necessary to use a PIN diode with a very low capacitance (C_T). To achieve negligible resistance during the ON state and high isolation during the OFF state, an MA4AGFCP910 PIN diode from MACOM Technology Solutions was selected as the switch. It has a series resistance of 5.2 Ω at 10 mA during the ON state and an ultralow capacitance value of 0.018 pF, providing high isolation during the OFF state. To achieve more accurate simulation results, it is recommended to use the touchstone s2p files of the PIN diodes for both the ON and Off-state conditions.

To switch the RF signal ON and OFF, a single-pole/single-throw (SPST) RF switch using a PIN diode is shown in Fig. 2b. The biasing circuit is implemented on the ground plane with proper care so that it will not affect the antenna performance. Three wide slots of 0.25 mm are formed, which divide the ground plane into three separate isolated regions, so that the two PIN diodes can be biased separately with respect to each other. Three DC-blocking capacitors are mounted across these slots to ensure proper DC separation and provide a low-impedance path to the RF signal. An RF choke inductor is added to the DC-bias lines to avoid the effect of DC-bias lines on antenna performance, as it provides high impedance to the RF signal. In addition, two inductors with the same value of RF choke inductor are added in the return path of the DC current. The capacitors and inductors used in the proposed design were obtained from Murata. The capacitors used (Murata GRM0225C1H5R0WA03) had a value of 5.0 pF, and the inductors (Murata LQW15AN2N2G80) had a value of 2.2 n In the ON state, PIN diodes were provided with a forward bias voltage of 1 V DC supply, and for the OFF state, no supply (0V) was provided.



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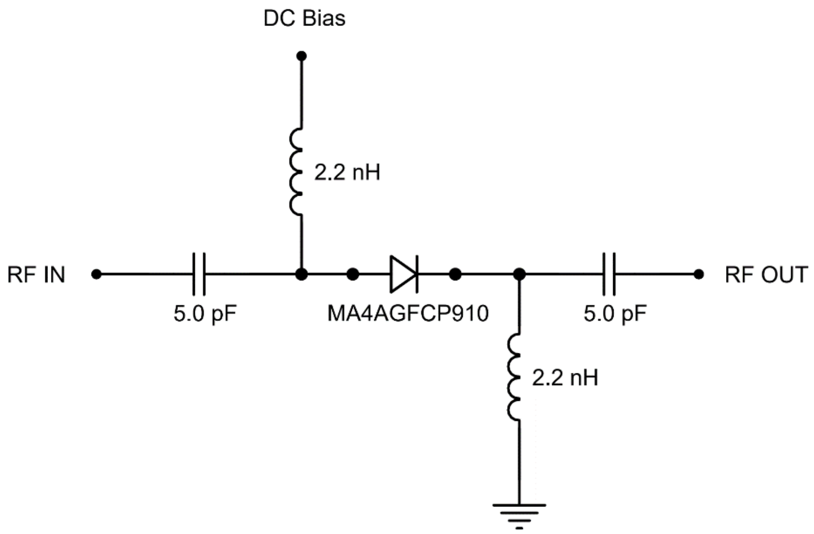


b

Fig. 2 – PIN diode equivalent model (a), DC biasing circuit (b)

2.3 Effect of Biasing Network

The biasing network affects the antenna performance parameters. To understand the effect of the biasing network on antenna performance, two designs, Design-1 and Design-2, were simulated using CST Microwave Studio.

Design-1: The main purpose of Design-1 is to study the impact of PIN diode on the performance of the antenna. Here the s2p files of the PIN diodes available from the manufacturer website have been incorporated in the CST simulation software. The antenna prototype was simulated in CST Design Studio, as illustrated in Fig. 3.

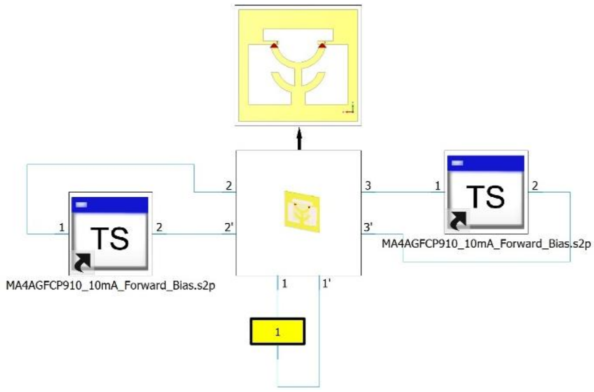


Fig. 3 – Antenna schematic (Design-1)

Table 2 – Comparison of Design-1 and Design-2

Mode	Design-1		Design-2	
	Resonance Frequency (GHz)	**Bandwidth**	**Resonance Frequency (GHz)**	**Bandwidth**
1	5.55	5.12-6.0 GHz (15.8 %)	5.34	4.99-5.77 GHz (14.5 %)
2	2.42	2.4-2.43 GHz (1.24 %)	2.41	2.39-2.43 GHz (1.66 %)
3	3.62 and 6.20	3.58-3.65 GHz (1.94 %) and 5.85-6.52 GHz (10.8 %)	3.55 and 5.82	3.51-3.58 GHz (1.97 %) and 5.53-6.12 GHz (10.1 %)

Design-2: In Design-2, the effect of the biasing network on performance of the antenna is examined in addition to the PIN diode effect studies in Design-1. Fig. 4 shows the antenna schematic in CST Design Studio, incorporating the s2p files of the PIN diode, in addition to the biasing inductors and capacitors.

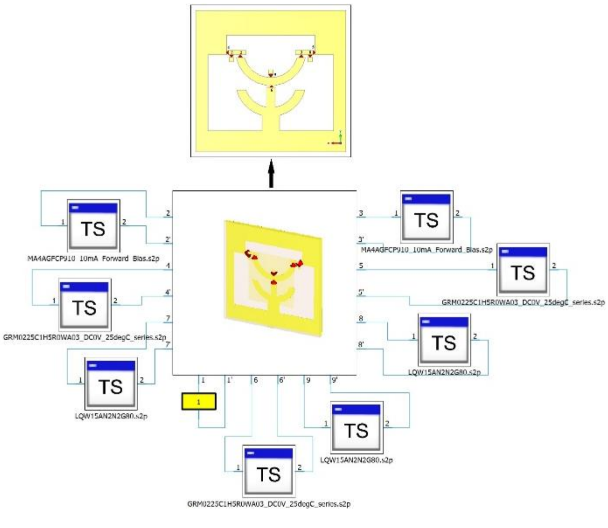


Fig. 4 – Antenna schematic (Design-2)

In the case of a microstrip antenna, each metallic structure has distributed resistance, inductance, and capacitance associated with it. The provision of slots also affects the effective capacitance and inductance, changing the resonance frequency to a lower value [26]. By introducing inductors and capacitors in the DC biasing network, the net capacitance and inductance change, which further affects the frequency at which the microstrip patch antenna resonates.

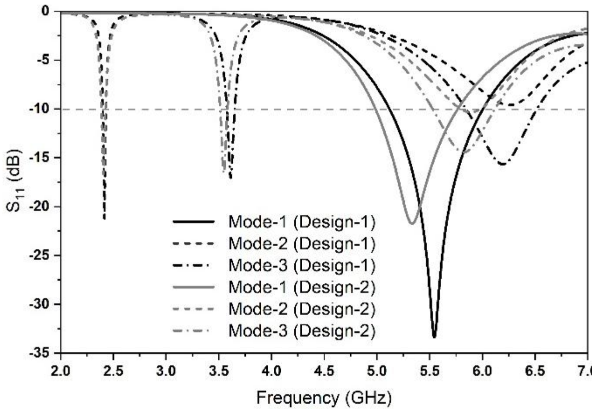
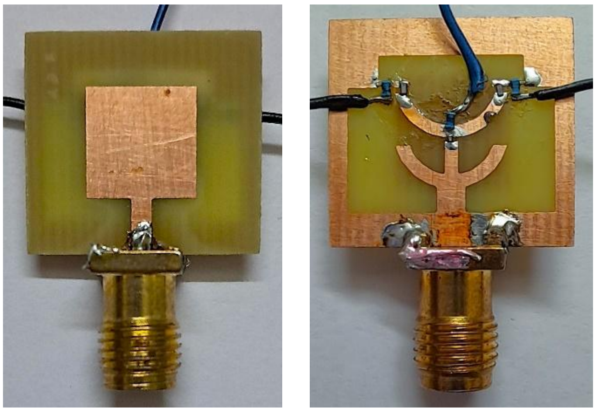


Fig. 5 – S_{11} in various operating modes for design-1 and design-2

Fig. 5 compares the simulated results of Design-1 and Design-2 for various operating modes. The results are presented in Table 2. The simulation results show that the reflection coefficients are in good agreement with $S_{11} \leq -10$ dB. The variation in the antenna resonance frequency for Design-2 is mainly due to the DC biasing components, which highlights the effect of the DC biasing network on the performance of the antenna.

3. RESULTS AND DISCUSSIONS

The fabricated antenna is shown in Fig. 6. It has a rectangular patch with dimensions of 4×4 mm^2 connected to a microstrip feed line having size of 4×1.5 mm^2. To feed the RF signal to the antenna, an SMA connector with a 50 Ω characteristic impedance was provided at the feed point. To measure the reflection coefficient (S_{11}), a Rohde & Schwarz ZVL13 Vector Network analyzer was used.



a b

Fig. 6 – Fabricated antenna prototype

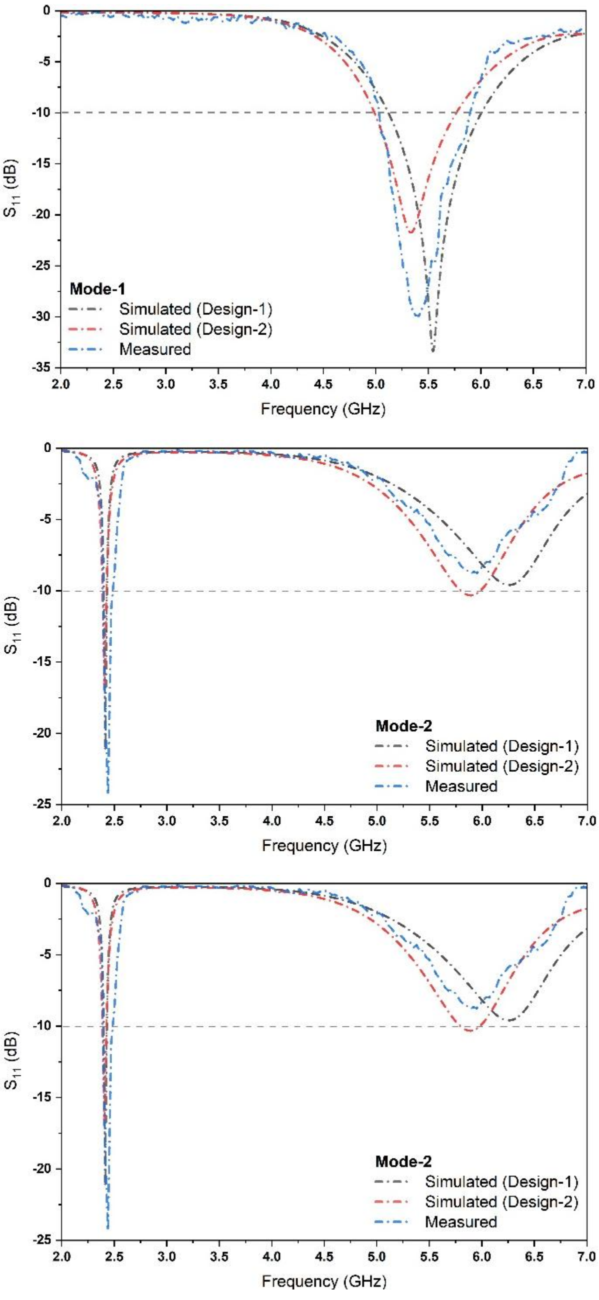


Fig. 7 – S_{11} of the antenna for various operating modes

Fig. 7 compares simulation and measurement of S_{11} parameters for each operating mode of the antenna, with strong correlation between them.

The distribution of surface current on both the top and bottom plane of the antenna were studied for various resonant frequencies. Fig. 8 depicts the distribution of the surface current at 2.42, 3.62, 5.55, and 6.2 GHz. The surface current path length changes based on the PIN diode operating mode, which results in a change in the operating frequency of the antenna.

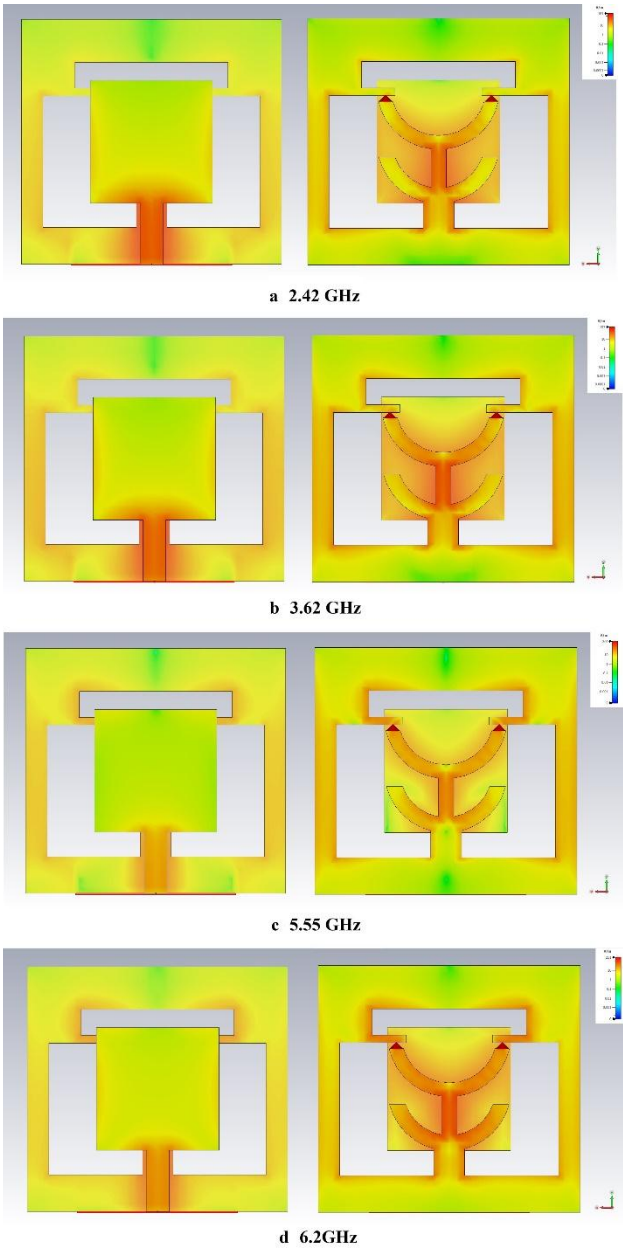


Fig. 8 – Antenna surface current distribution

When the antenna operates in mode-1 (SW1 and SW2 are ON), the patch current is minimal and flows through the top side of the ground plane, leading to resonance at 5.55 GHz. During mode-2, when both switches are in the OFF state, the surface current is maximum in the feedline section and along the edges of the patch. The patch current couples to the center of the ground plane and then starts flowing through the side arms, causing the antenna to resonate at 2.42 GHz. In mode-3, the antenna exhibits dual-band resonance (3.62 and 6.2 GHz). In the case of 3.62 GHz, the pattern of the surface current on the patch is similar to that of the 2.42 GHz case, but with a stronger concentration on the ground plane. In the case of 6.2 GHz, the concentration of the surface current on the patch side is minimal and has a strong concentration on the top side of the ground plane.

The simulated 3D far-field radiation patterns of the antenna at 2.42, 3.62, 5.55, and 6.2 GHz are shown in Fig. 9. At these frequencies, the antenna gain is – 6, – 0.65, 2.95, and 2.56 dBi, respectively. The simulated 2D radiation patterns for both the *H*-plane and *E*-plane are illustrated in the Fig. 10. The *H*-plane patterns are omnidirectional, while the *E*-plane patterns exhibit a dipole-like radiation pattern. The antenna maintains a nearly stable radiation pattern in the *H*-plane across all frequencies, while there is a slight variation in the radiation pattern in the *E*-plane.

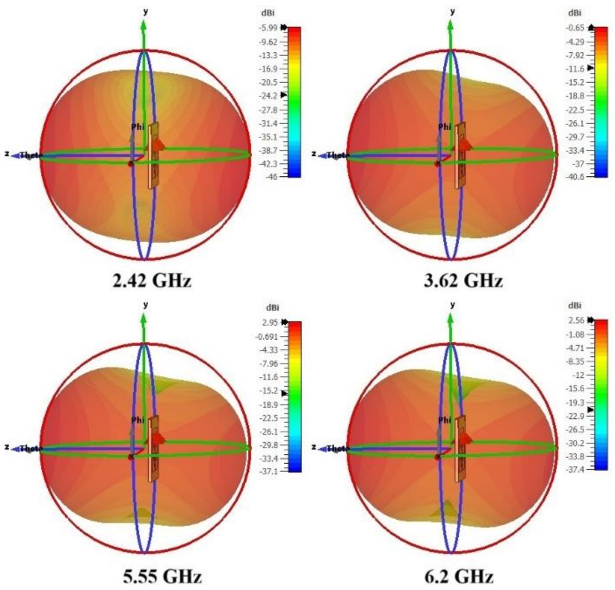
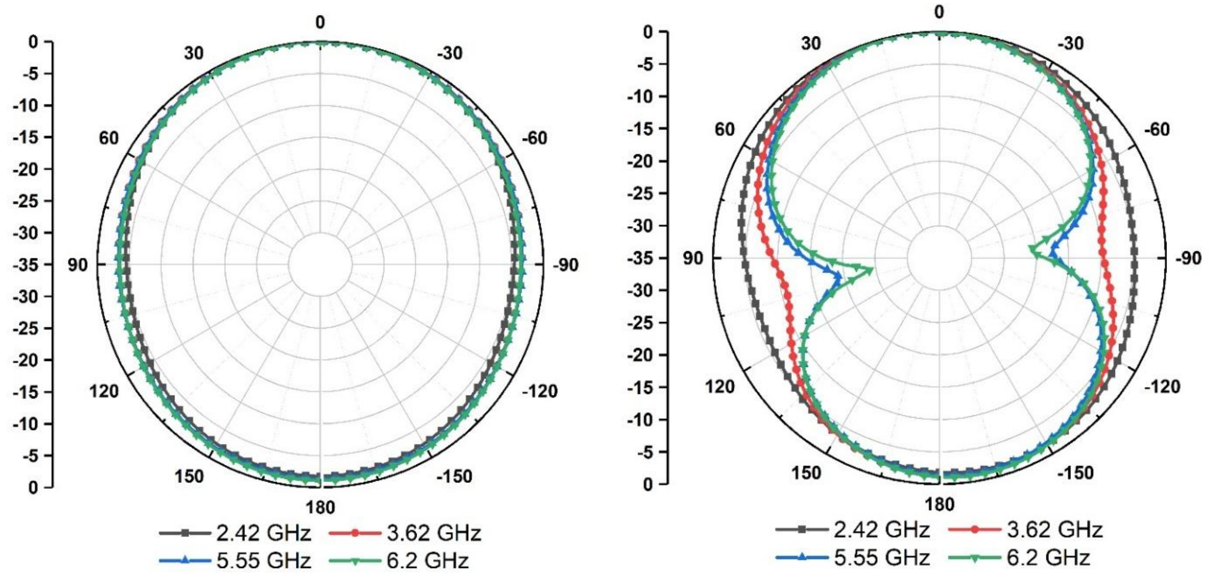


Fig. 9 – Simulated 3D radiation pattern



a b

Fig. 10 – Antenna radiation patterns: *H*-plane (a), *E*-plane (b)

Table 3 – Comparison of the proposed antenna with existing works

Ref. №	Size (mm^3)	Reconfigurable Technique	Number of modes	Operating Frequency (GHz)	Peak Gain (dBi)	DC Bias Circuit
[8]	40 × 40 × 1.5	Varactor Diode (1)	Continuous tuning	1.4 to 2.9	2.32	Yes
[9]	20 × 20 × 0.8	PIN Diode (3)	3 – All single band	2.4; 3.5; 5.2	NA	Yes
[10]	30 × 30 × 0.762	PIN Diode (2)	3 – Two single and one dual band	3.8; 4.5; 5; 5.9	4.64	Yes
[11]	17 × 15 × 1.6	PIN Diode (3)	4 – Two dual and two triple band	5.38; 6.76; 8.82	4.28	No
[12]	35 × 40 × 1.6	PIN Diode (3)	6 – All single band	4.36; 4.47; 4.96; 5.66; 5.81; 6.01	8.17 dB	Yes
[22]	48 × 24 × 1.6	PIN Diode (2)	4 – Three single and one dual band	1.9; 2.4; 3	NA	Yes
[23]	80 × 50 × 1.6	PIN Diode (3)	3 – Two single and one dual band	433; 868; 915	2.1	Yes
[24]	40 × 1.4 (Circular Patch)	PIN Diode (5)	6 – All single band	1.82; 2.18; 2.23; 2.35; 2.41; 2.46	7.10	Yes

[25]	30 × 27 × 1.6	PIN Diode (3)	4 – All single band	3.35; 3.78; 4.32; 4.55	4.0	Yes
This Work	16 × 17 × 0.8	PIN Diode (2)	3 – Two single and one dual band	2.42; 3.62; 5.55; 6.2	2.95	Yes

NA – Not Available

The outcomes of the proposed research are compared with those of recent relevant studies in Table 3. The proposed design overcomes the significant challenge of miniaturization through the implementation of a defected ground plane. Table 3 shows how the proposed microstrip patch antenna design provides an innovative antenna with a miniature size, number of operational frequency bands, and usefulness for modern wireless communication applications.

4. CONCLUSIONS

A miniaturized microstrip patch antenna with size of 16 × 17 × 0.8 mm^3 is proposed for frequency reconfiguration at four different bands. The antenna is miniaturized by using the concept of defected ground structure (DGS). A novel defected ground plane has been proposed for achieving the desired miniaturization and by using PIN diodes as switching elements the antenna is able to operate in three different modes, two single band modes and one double band mode. The PIN diode biasing network affects the resonance frequency of the antenna. The proposed antenna functions within the frequency ranges of 2.4-2.43 GHz, 3.58-3.65 GHz, 5.12-6.0 GHz, and 5.85-6.52 GHz. The measured reflection coefficient is in good correlation with the simulated one. The proposed frequency reconfigurable antenna is a prominent contender for switchable 2.4 GHz Wi-Fi, n-78, 5G Wi-Fi and n-96 band applications.

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Проєктування мініатюрної мікросмужкової антени з можливістю реконфігурації частоти з використанням PIN-діодів та дефектної заземлювальної структури для сучасного бездротового зв'язку

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Представлено мікросмужкову патч-антену з можливістю реконфігурації частоти та модифікованим дефектом у заземленій площині. Реконфігурація частоти досягається за допомогою двох PIN-діодів, вбудованих у заземлену площину у відповідних місцях. Для живлення PIN-діодів було включено мережу зміщення постійного струму. Також представлено вплив мережі зміщення постійного струму на характеристики резонансної частоти антени. Змінюючи стани PIN-діодів, антена може працювати в трьох різних режимах з резонансом у чотирьох різних діапазонах частот: 2,42 ГГц (Wi-Fi), 3,62 ГГц (n-78), 5,55 ГГц (5G Wi-Fi) та 6,2 ГГц (n-96). Запропонована антена має невеликий розмір 16 × 17 мм^2 та виготовлена на недорогій підкладці FR-4. Була досягнута сильна кореляція між результатами моделювання та вимірювання коефіцієнта відбиття з $|S_{11}| \le -10$ дБ у всіх трьох режимах роботи запропонованої конструкції, що підтверджує її достовірність. Мініатюрний розмір антени робить її корисною для сучасного бездротового обладнання, де головною проблемою є обмежений простір.

Ключові слова: Мініатюрна, DGS, Патч-антена, Переналаштування частоти, PIN-діод.