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A novel PIN diode-based frequency reconfigurable patch antenna with switching between the mid-5G and high-5G frequency band

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Abstract

This research article represents the design of a simple, smaller, and novel frequency reconfigurable patch antenna for 5G communication using PIN diodes. This antenna operates in both mid-5G and high-5G bands. The antenna is intended to operate in eight distinct modes with three PIN diodes in 5G wireless communication covering 27.46–50 GHz of high-5G band (range n257/n258/n260/n261/n262) and frequencies of the 3–6 GHz of mid-5G band (range n77/n78/n79/n46). The antenna has an overall size of 20 mm × 25 mm × 1.6 mm and is placed upon a low-cost FR4 substrate. A higher radiation efficiency from 75% to 98% is achieved in all the different modes. The resonant frequencies are around 3.46, 4.43, 5.83, 31.8, 35.5, and 46 GHz in different modes of operation. Different switching statuses have been carried out in this research work and their performances have also been illustrated in the form of surface current distribution in different resonant frequencies. The simulated and measured results are compared to highlight its proposed design operation.

Introduction

The high-5G band (24–40 GHz) and the mid-5G band (1–6 GHz) are both in significant demand in the ongoing technology of 5G wireless communications. This mid-band frequency is comparatively lower in speed than high-band 5G but can offer a higher coverage radius. So, the basic need to cover both the bands with a single antenna element may be a challenge to researchers in the near future. So, the use of different switching elements like electronic switches, thyristors, transistors, PIN diodes may give strong support to overcome this challenge because these switching devices may lead to the reconfigurability of the frequencies. If we look into a few recent papers on this type of antenna, a small V-shaped long-wire antenna is proposed in [1] using two PIN diodes and RF choke to operate in five different narrow bands between 4.5 and 6 GHz in different switching status. A high gain between 3.4 and 6 dB is found in the antenna. A highly efficient (85%) antenna is reported in [2] which also produces five different bands using a single diode. With forward bias condition, it resonates at 2.4 and 5.3 GHz, but when it is biased reversely it shifts towards 3.3 and 5.9 GHz and when no bias is applied it produces resonance at 4 GHz. A dual-band frequency reconfigurable MIMO antenna is suggested in [3] which uses one diode to operate at 3.35–4.60 and 4.93–5.19 GHz when the diode is ON, with an L-stub in the ground plane to reach the optimum bandwidth. It achieves an efficiency of 65% and 75%, respectively, in port-1 and port-2. While a single varactor diode-based antenna is highlighted in high-band 5G in [4] to switch between two bands of 28 and 38 GHz center frequency. When the diode is ON, the aerial functions at 38 GHz, but when it is OFF, it runs at 28 and 38 GHz. A multimode antenna is presented in [5] using two PIN diodes, three capacitors and an inductor for frequency reconfiguration for multiple applications like mid-band 5G, ISM band applications, WLAN. Upadhyay et al. [6] suggested a reconfigurable antenna array using two PIN diodes operating in four different modes offering multiband frequencies with a high peak gain suitable for vehicular communication. Upadhyay et al. [7] proposed for another reconfigurable antenna having the application of an intelligence transport system using PIN diodes. A co-planar waveguide hexagon antenna is presented in [8] for cognitive radio communication using PIN diode offering frequency hopping from 3.75 to 12.67 GHz. Another UWB adjustable antenna is reported by Abdulhameed et al. [9], consisting of two PIN diodes obtaining four different modes of frequencies. A rectangular patch antenna with a C-slot is presented by Al-Yasir et al. [10] with a polarization reconfigurable technique to work it in multiple 5G bands within sub-6 GHz frequency range. For the mm-wave mobile phone to function at 28 and 38 GHz frequency [11], a frequency-configurable antenna array has been developed on Rogers

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RT Duroid substrate material. Ghaffar et al. [12] suggested a triangular reconfigurable antenna in sub-6 GHz frequency using two PIN diodes to cover 2.31–4.4 GHz. Four PIN diodes are used by Dildar et al. [13] to cover nine different bands for the sub-6 GHz band as well as IoT applications for smart cities. An antenna having circular polarization encountering super wide band from 2.6 to 22 GHz is presented by Kumar et al. [14]. Jin et al. [15] suggested an antenna that is differentially fed having two different substrates having a separation of 2.5 mm air gap using four PIN diodes applicable in wireless LAN and mid-5G band. A switchable slot has been inserted inside a rectangular slot by Boufrioua [16] to insert a single PIN to switch between two narrow bands in mid-5G frequency band. Another reconfigurable antenna is suggested by Iqbal et al. [17] operating in four different modes with three PIN diodes having high radiation efficiency of over 82% and high gain applicable for mid-band 5G/4G/4.5G/LTE/WIMAX/WLAN applications. Jin et al. [18] and Ullah et al. [19] also suggested the same using four PIN diodes and two PIN diodes, respectively. In Rizvi Jarchavi et al. [20, 21], the antenna dimensions are very near to each other. In Rizvi Jarchavi et al. [20], triple band is achieved in only high-band 5G but in Rizvi Jarchavi et al. [21], dual band response is found in mid-band 5G. So, switching devices may be embedded into these for flexible applications. In Jarchavi et al. [22], one PIN diode is acting as a switching device, which produces four different operating bands with an efficiency of 80%.

The above discussions show that the reconfigurable antenna is in high demand as different applications can be accessed by using switching devices in a single antenna element.

The challenges for a researcher or a microwave engineer to design an antenna in upcoming years are as follows:

(i) Designing an antenna to achieve multiple frequency bands for different applications.
(ii) To use a proper switching device to operate in different bands.
(iii) Designing an antenna for 5G wireless applications that operates in both the mid-5G band (3–6 GHz) and high-5G band (24–40 GHz) is also difficult.
(iv) To make the design as simple as possible.

The antenna proposed in this article uses three PIN diodes as switching devices to operate the antenna in eight different modes. When all the diodes are OFF, the antenna is functional in the mm-wave 5G band from 27.46 to 50 GHz. It also operates in different narrow bands of sub-6 GHz 5G channel in the remaining seven modes. So, the challenge of using a single antenna in both mid-band and high-band 5G is achieved in this work. This technology helps the antenna to achieve an enhanced efficiency of about 98%.

Section 2 discusses the antenna designing procedure and the proper placement of the PIN diodes. In Section 3, all the simulated and measured data are discussed and compared. A comparison table with recent works related to this work is also prepared in Section 4. The paper is concluded in Section 5.

Antenna design, analysis, and procedure

The proposed antenna has been placed on a low-cost FR-4 substrate. The measured volume of the optimized antenna is 20 mm × 25 mm × 1.6 mm. So, the antenna size is also tiny compared to many proposed designs. In the first step, a simple rectangular patch is designed to resonate at mm-wave frequency. So, if it is intended to function at mid-5G band, the patch length and width will increase. So, an inverted U-shaped patch surrounds the rectangular patch for that purpose. In the next step, the PIN diodes are placed to connect these patches as shown in Figure 1(a) and (b).

The equivalent RLC circuit of the PIN diode is shown in Figure 1(c) for different switching statuses. In “ON” status, the resistance shows a low value while in “OFF” status it exhibits Megaohm range. The simulation process has been carried out using ANSYS Electronics Desktop HFSS 21.0 version [23]. The antenna parameters are calculated from the base formulas [24] and values are optimized during simulation. The optimized parameters from Figure 1(a) are Ws = 20 mm, Ls = 25 mm, Wp = 8 mm, Lp = 3 mm, Lf = 11.75 mm, Wf = 2 mm, L1 = 18 mm, L2 = 23 mm, L3 = 2.75 mm, L4 = 5.75 mm, and L5 = 4.25 mm.

Proper placement of the PIN diodes is one of the essential things in this research. Whenever no diodes were placed, the antenna operated only in mm-wave applications. So, for the proper placement of PIN diodes, surface current distribution (SCD) is studied in 3.3, 4.6, and 5.5 GHz found in Figure 1(f)(i-iii), respectively. In the places where the highest amount of currents are found [the red portion in circle of Figure 1(f)], the diodes are placed exactly there to make it conduct in that particular frequency as a conductor. The PIN diode used to fabricate this antenna is MA4PH301. It can operate up to 6 GHz frequency as a RF switch, but it gets cut off beyond this limit. So, it provides good switching performance up to 6 GHz. This particular PIN diode is used for working the antenna in the mid-5G band.

The biasing arrangements of the PIN diodes are shown in Figure 1(g) and (h). In Figure 1(g), the biasing arrangement for D1 is shown. A basic series topology is applied to switch ON the diode to minimize the insertion loss. The DC bias is provided but the diode D1 will only switch ON when it gets the desired frequency signal from V_G. This frequency may be determined by Radio Frequency Coil (RFC). The DC Blocking (DCB) capacitor will block the dc voltage to flow towards the V_G [25]. In Figure 1(h), as the diodes D2 and D3 are physically close to each other, so shunt topology comes into play. In this biasing two DC voltage is applied for two diodes but only one RF generator voltage V_G is used. D2 will be ON when V_G will provide its desired frequency while D3 will remain OFF. Similarly, D3 will be ON when V_G will provide its desired frequency while D2 will remain OFF. All the diodes will obtain the V_G signal from the feedline of the antenna where Z_0 is the characteristics impedance of the transmission line and also the antenna impedance is supposed to be the same in desired frequency for perfect impedance matching.

Results and analysis

Prototype testing of the PIN diode as a RF switch

Before implementing the PIN diode, the testing is done to make sure about efficient performance of the PIN diode as RF switch to meet the objective. In the simulation process, a simple microstrip line filter was designed upon FR4 base with an equivalent block of specified PIN diode placed in the middle of the line, and two DCB capacitors (22 pF) were integrated to block DC from DC bias to the RF port. In high frequencies, it exhibits a small impedance ($X_c = 1/2\pi fC$) around 1.2057 Ω in 6 GHz behaving almost like a short circuit that allows the RF signal to pass from one port to another. The simulated structure is shown in Figure 2(a) with the

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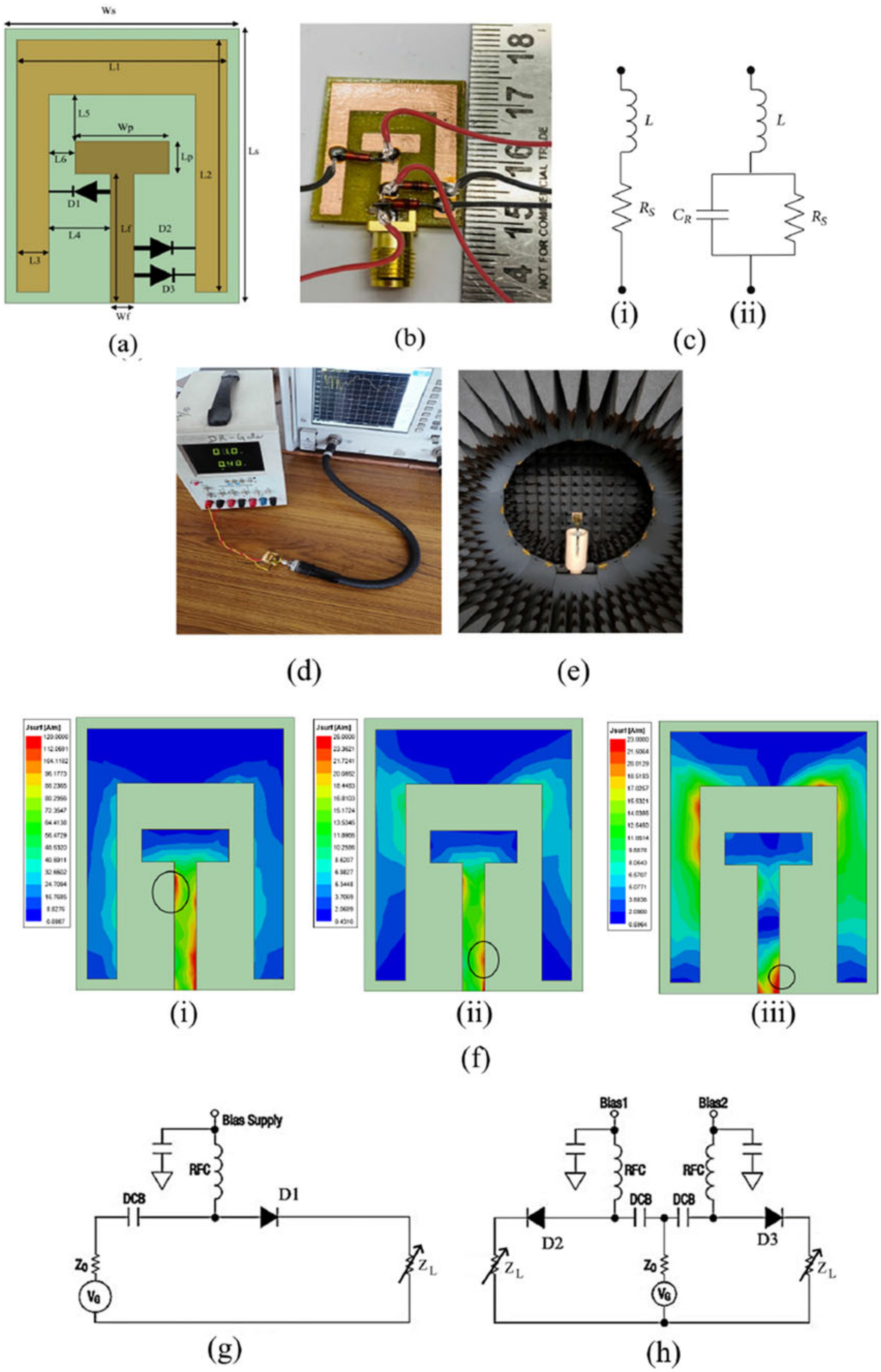

Figure 1. Proposed antenna design: (a) simulated, (b) fabricated, (c) equivalent circuit of PIN diode (i) ON state and (ii) OFF state, (d) antenna measurement with VNA, (e) antenna in the anechoic chamber during test, (f) surface current distribution without PIN diodes in (i) 3.3 GHz, (ii) 4.6 GHz, and (iii) 5.5 GHz frequencies, (g) biasing arrangement for D1, and (h) biasing arrangement for D2 and D3.

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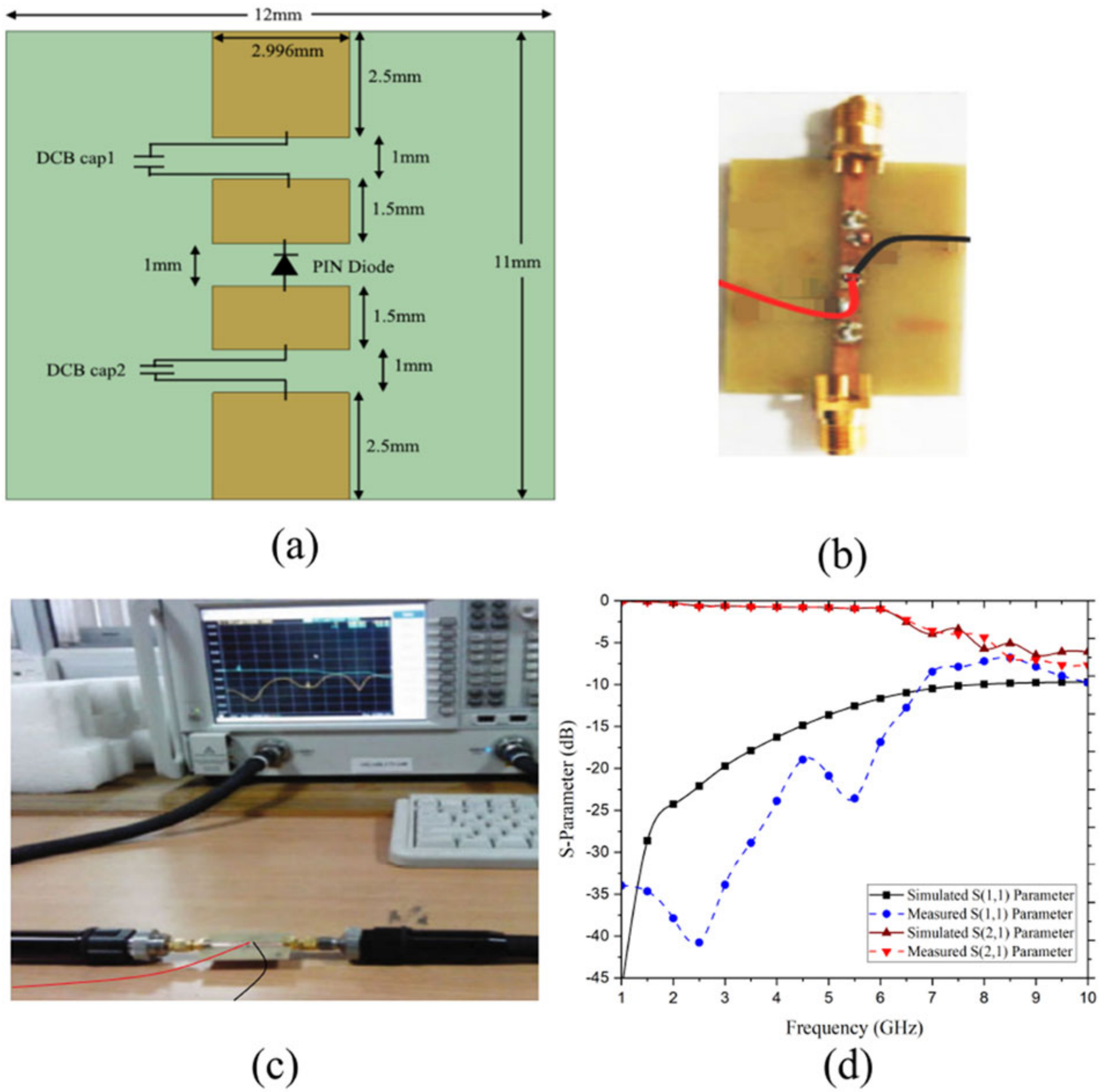

Figure 2. PIN diode testing: (a) simulated structure for PIN diode testing, (b) fabricated microstrip line filter with PIN diode and DCB capacitors, (c) PIN diode under testing, and (d) simulated and measured result.

required measurements and the fabricated prototype is shown in Figure 2(b). The PIN diode testing setup is illustrated in Figure 2(c). The testing of the PIN diode has been performed as per standard practice [26].

Both the results of measurements and software simulation are shown in Figure 2(d), while the PIN diode is ON. In this figure, only S(1,1) and S(2,1) Parameters are shown from 1 to 10 GHz. In both the simulation and prototype testing, isolation loss (S(1,1) Parameter) is more than 12 dB till 6.39 GHz. But most importantly, the insertion loss is below 0.5 dB up to 2.2 GHz and it is in between 0.5 and 1 dB from 2.2 to 6.02 GHz as shown in measured data of the S(2,1) Parameter, while in simulation it was below 0.5 dB till 2.43 GHz and it was below 1 dB from 2.44 to 6.14 GHz. After these ranges, the insertion loss falls significantly which is not permissible to use practically for switching. So, testing of the PIN diode gives us strong support to perform with the proposed antenna as a RF switch.

S-Parameter with surface current distribution

In this section, a detailed analysis of the reflection coefficient (S11-Parameter) has been carried out in all the modes of operation. As already discussed in the above section, three PIN diodes are used, so the number of modes is $2^3 = 8$. All the bandwidths have been taken below the margin of −10 dB from the S11-Parameter graph. The −10 dB reference level signifies that a minimum of 90% of the incident power is delivered to the antenna and the remaining 10% is reflected to the input side. So for good performance of the antenna, more than 90% of the power must be delivered to the antenna.

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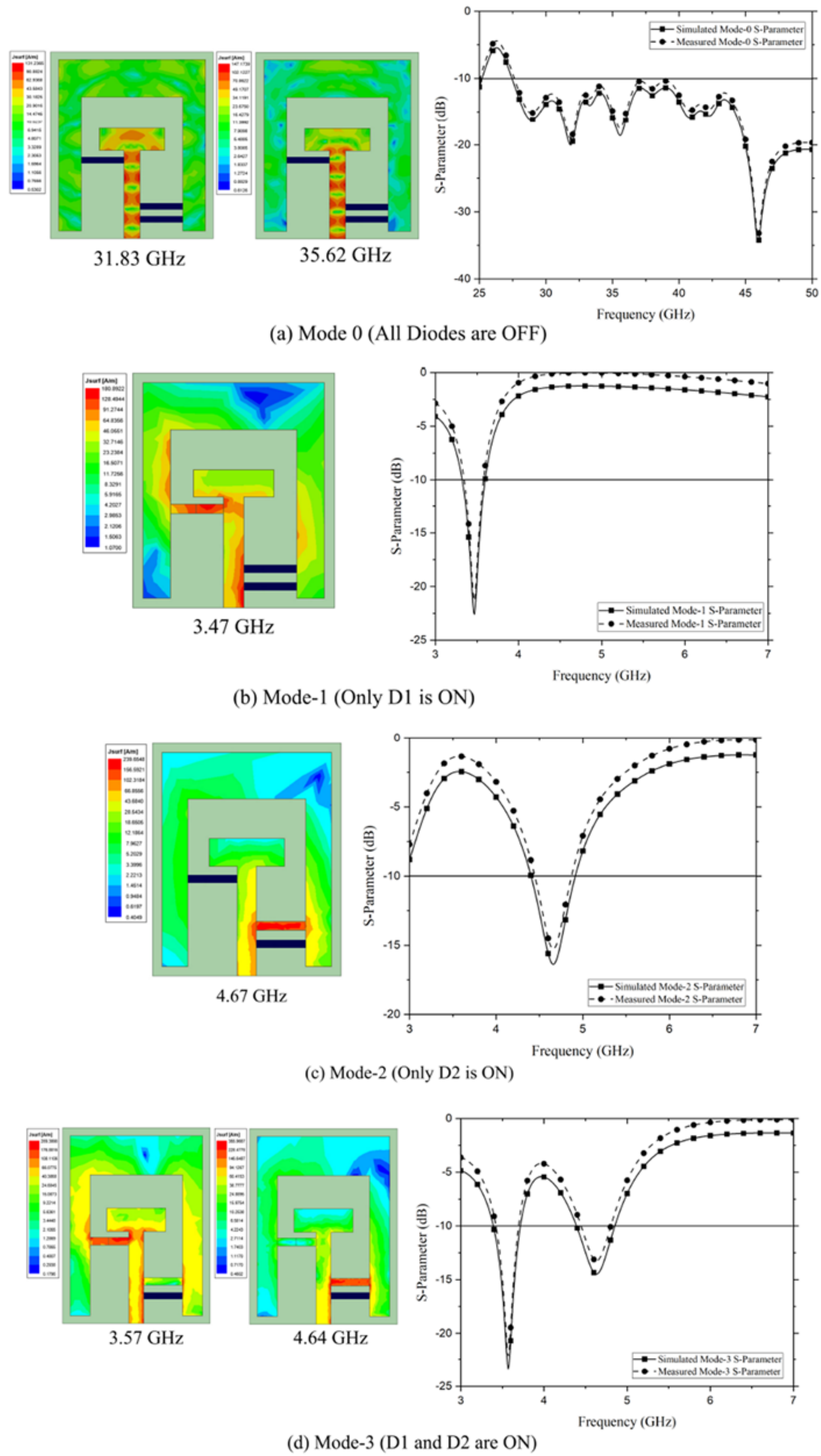

Figure 3. Variation of surface current distribution, S-Parameter (S11) of proposed antenna during mode-0 to mode-3 of PIN diodes.

Details operation of each mode is elaborated below:

- In Mode-0, when all the diodes are OFF, the antenna can be applicable in mm-Wave applications producing a super wide-band (SWB) of 27.46–50 GHz (22.54 GHz).
- In Mode-1, when only diode D1 is ON, a narrow band of 300 MHz (3.3–3.6 GHz) is produced.
- In Mode-2, when only diode D2 is ON, a narrow band of 520 MHz (4.4–4.92 GHz) is produced.
- In Mode-3, when diodes D1 and D2 are ON, two narrow bands

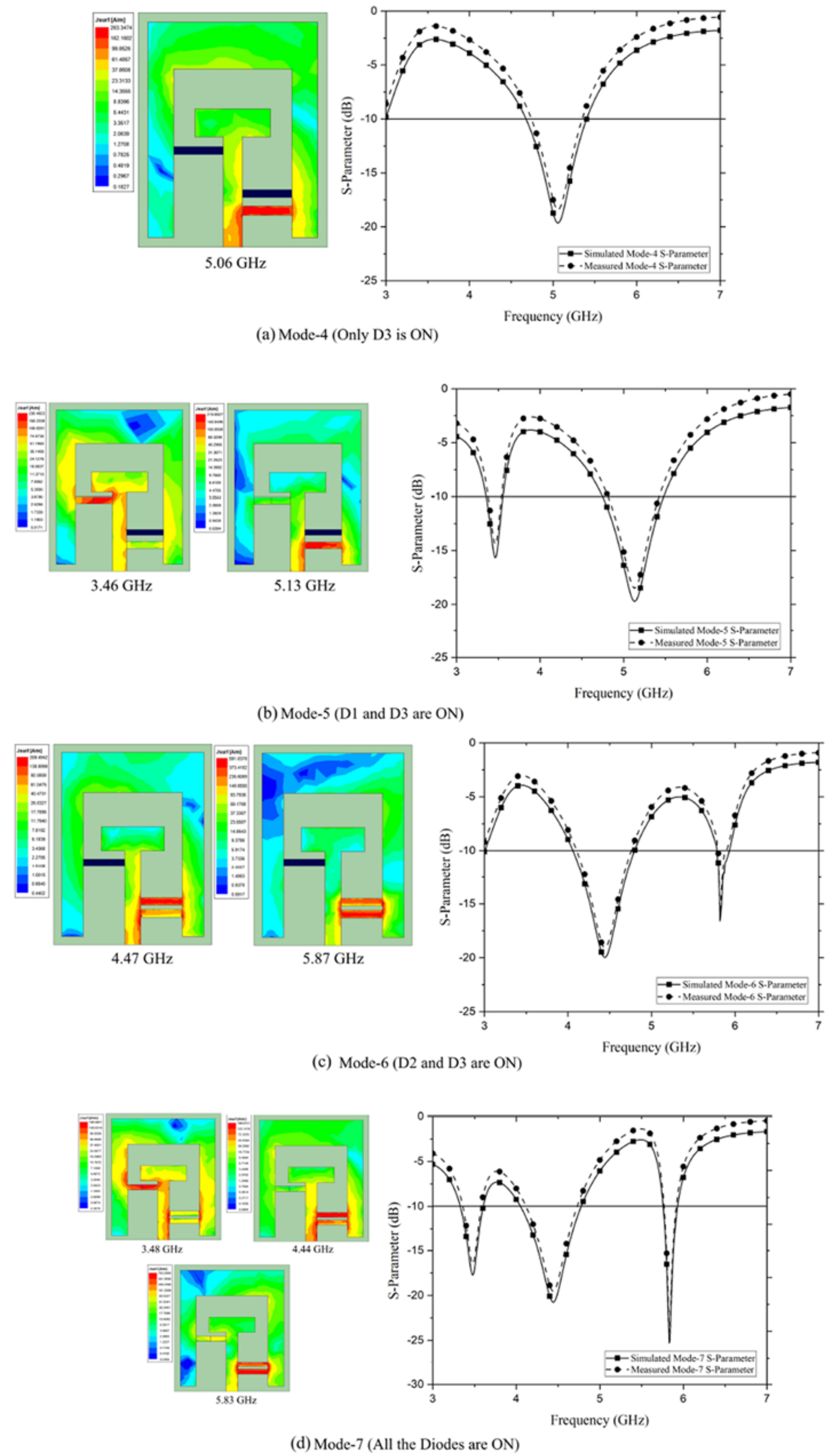

Figure 4. Variation of surface current distribution, S-Parameter (S11) of proposed antenna during Mode-4 to Mode-7 of PIN diodes.

of 320 MHz (3.4–3.72 GHz) and 500 MHz (4.3–4.8 GHz) are produced.

- In Mode-4, when only diode D3 is ON, a narrow band of 720 MHz (4.68–5.4 GHz) is produced.

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- In Mode-5, when diodes D1 and D3 are ON, two narrow bands of 200 MHz (3.35–3.55 GHz) and 750 MHz (4.75–5.5 GHz) are produced.
- In Mode-6, when diodes D2 and D3 are ON, two narrow bands of 750 MHz (4.05–4.8 GHz) and 130 MHz (5.8–5.93 GHz) are produced.
- In Mode-7, when all the diodes are ON, three narrow bands of 300 MHz (3.3–3.6 GHz), 770 MHz (4–4.77 GHz), and 170 MHz (5.76–5.93 GHz) are produced.

The reflection coefficient (S11-Parameter) with their respective SCD at different frequencies are shown in Figures 3 and 4 for Mode-0 to Mode-3 and Mode-4 to Mode-7, respectively. It displays the effect of PIN diodes and their switching status. In every mode of operation, when the diodes are ON, maximum current flows through them, while in OFF condition, no current is seen through the diodes. This significant switching of the obtained band from Mode-0 to mid-5G band is due to the change of the path in currents as well as the diode specifications and its biasing.

In Mode-0 operation, the biasing is kept OFF to all the PIN diodes permitting the antenna to achieve a high-5G band (range n257/n258/n260/n261/n262). The proper placings of PIN diodes play a vital role in the variation of the antenna's electrical length. Due to this technology based on electrical length variation using switching finds out a new way to use a single-element antenna in both high-5G and mid-5G bands covering a wide range of frequency bands (n77/n78/n79/n46/n257/n258/n260/n261/n262 bands).

Radiation pattern analysis

Five different resonant frequencies have been studied for the analysis of radiation patterns. In every resonant frequency, it has been seen that the antenna produces radiations, which are omnidirectional in nature. Figure 5(a–d) show the patterns in two different resonant frequencies in Mode-0 (E-Plane and H-Plane for both 31.8 and 35.53 GHz). The maximum gains of 3.7 and 4.94 dB are achieved at 31.8 and 35.53 GHz, respectively. The other three resonant frequencies being analyzed here are in the sub-6 GHz frequency band. These are 3.46, 4.43, and 5.83 GHz. Omni-directional patterns have been achieved with maximum gains of 4.78, 4.4, and 4 dB, respectively, as shown in Figure 5(e–j).

Radiation efficiency and gain

The radiation efficiency is another important parameter for a patch antenna. It shows the proportion of gain to directivity. All eight modes of operation of the proposed antenna have been studied which support a good result. In Mode-0, the range of efficiency is achieved from 75% to 88%. All the other modes of mid-band 5G show an efficiency of 78% to 98% (combined range of Mode-1 to Mode-7). The radiation efficiency graphs are shown in Figure 6(a) and (b). The feature of high efficiency is well supported by achieving high gain in every mode of operation. Figure 6(c) and (d) elaborate the gain of the optimized antenna in all the operational modes. In Mode-0, a gain of 3.5–5.3 dB is found in simulation and measurement as prepared in Figure 6(c). In other modes of operation, the gain of the optimized antenna ranges between 3.5 and 4.5 dB as displayed in Figure 6(d).

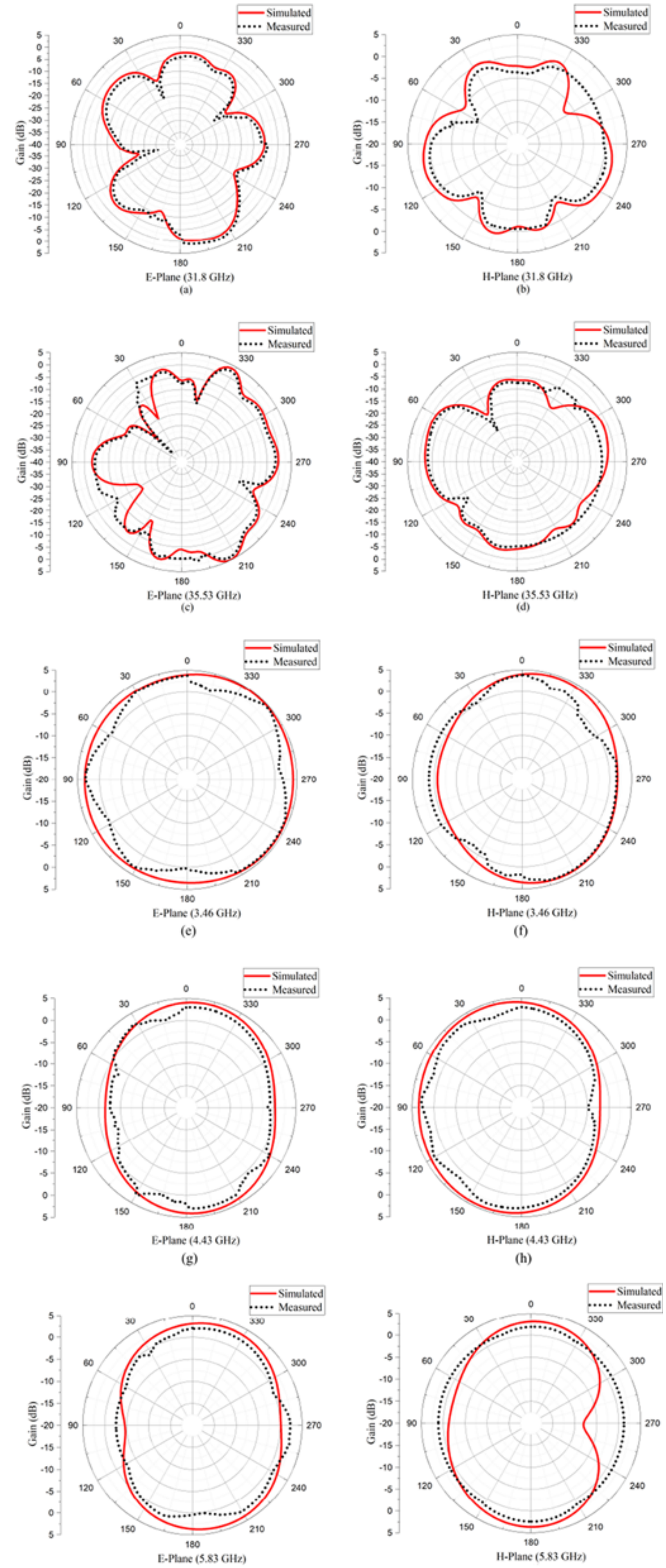

Figure 5. Radiation patterns at (a) E-Plane (31.8 GHz), (b) H-Plane (31.8 GHz), (c) E-Plane (35.53 GHz), (d) H-Plane (35.53 GHz), (e) E-Plane (3.46 GHz), (f) H-Plane (3.46 GHz), (g) E-Plane (4.43 GHz), (h) H-Plane (4.43 GHz), (i) E-Plane (5.83 GHz), and (j) H-Plane (5.83 GHz)

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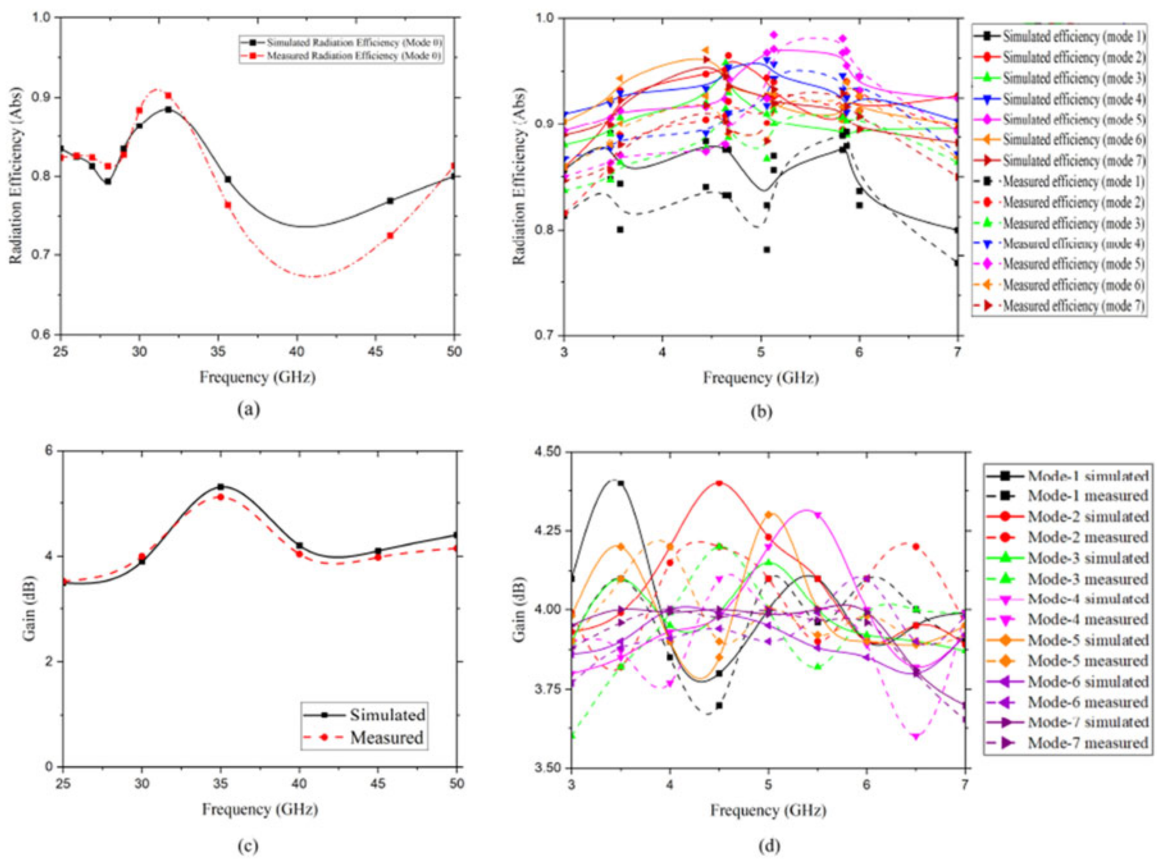

Figure 6. (a) Radiation efficiency in Mode-0, (b) radiation efficiency in Mode-1 to Mode-7, (c) gain in Mode-0, and (d) gain in Mode-1 to Mode-7.

Table 1. Table of comparison

Ref. No.	Antenna size (mm^3)	No. of PIN diodes	No. of (m)	No. of (h)	Efficiency (%) (max)	Max. gain (dB)	Max. pBW (%)
[6]	50 × 50 × 1.57	2	14	0	NP	3.4	16.3
[7]	26 × 49 × 1.6	1	11	0	NP	3.95	18
[12]	30 × 30 × 1.9	2	5	0	90	NP	7.2
[13]	40 × 32 × 1.6	4	9	0	84	3.6	28
[15]	100 × 100 × 5.7	4	2	0	85	>1.5	11.9
[18]	50 × 50 × 1.6	4	2	0	NP	4.2	33
[19]	37 × 35 × 1.6	2	4	0	>85	1.98	>10
[22]	35 × 25 × 0.79	1	4	0	80	8	NP
PD	20 × 25 × 1.6	3	12	1	98	5.3	71 (h), 17(m)

PD denotes proposed design, NP denotes not provided, pBW denotes percentage bandwidth, (h) denotes high-5G band, and (m) denotes mid-5G band.

Comparison

The proposed work has been compared with the recent related works that have been summarized in Table 1. This comparison shows that the challenge to achieve both the mid-5G band and high-5G band using PIN diode is achieved.

Table 1 is also evidence that the suggested antenna outperforms the antennas of currently published articles in the field of antenna size, and number of bands for flexibility in uses in both the specified bands having high efficiency and reasonably high gain.

Conclusion

In this paper, a unique and novel design has been proposed. The proposed antenna works in both, mid-5G band and the high-5G band of high-speed 5G wireless communication. The proposed antenna has the property of frequency reconfigurability using three PIN diodes at different places to switch the antenna at different frequency bands (n77/n78/n79/n46/n257/n258/n260/n261/n262). Using this property, the challenge of using only one antenna to work in both bands of 5G has also been overcome. So, flexibility

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for different applications is also a significant part of this antenna. Design simplicity and low cost also add more flavors to this. Also, it is possible to claim that the suggested antenna produced excellent efficiency from 75% to 98% and high gain of around 4–5.3 dB.

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Competing interests. The authors have no competing interests to declare.

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