Research Article

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Design and implementation of a frequency reconfigurable antenna using PIN switch for sub-6 GHz applications

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Abstract: The future of 5G New Radio development has many significant concerns. We present and investigate a frequency-reconfigurable antenna based on a PIN diode to overcome the working frequency band issue. The dimensions are 30 mm × 20 mm × 1.6 mm, built on material substrate (FR-4) with a relative permittivity of $\varepsilon_r = 4.4$. Two switches allow frequency reconfiguration in the antenna, giving us three operation modes. The design in mode 1 (SW1 = Off and SW2 = Off) covers a 4.6 GHz band. The proposed design in mode 2 resonated at 2.7 and 4.8 GHz (SW1 = On, SW2 = Off or SW1 = Off, SW2 = On), while the design in mode 3 operated at 3.6 GHz (SW1 = On, SW2 = On). Before fabrication, the proposed design is simulated by the Computer Simulation Technology microwave studio software. The presentation and discussion of the radiated pattern and S parameter demonstrate the practicability of the proposed design. The design module's dimensions and performance are both precisely appropriate. The results indicate a good agreement between both simulation and experimental findings.

Keyword: reconfigurable antenna, sub-6 GHz 5G applications

1 Introduction

The 5G mobile network, which uses the band of sub-6 GHz, promises to increase network capacity while delivering faster and more dependable communication services. Due to their adjustable frequency selectivity, reconfigurable antennas are essential for wireless applications and electronic surveillance [1].

Key benefits of fractal antennas include their small dimension, compliance with impedance, excellent directivity, and broadband and multiband responses [2,3]. Antenna researchers can employ a range of reconfiguration strategies when creating reconfigurable antennas. However, the complexity of these designs is another factor to be considered. Complexity increases dramatically in unwanted loss and costs [1]. Some strategies have been implemented to simplify any reconfigurable antenna system while retaining reliability [4–9]. Most of these methods are based on using different techniques or models.

This is already widely recognized in other academic domains [10]. Antenna designers are faced with challenging questions in designing reconfigurable antennas. The design procedure should consider many parameters, such as achieving an effective gain with an excellent impedance match and stable radiation. The reconfiguration property and method must be chosen at the start of the design procedure for constructing a reconfigurable antenna. A reconfigurable antenna can have four reconfiguration properties. An antenna may be able to alter its operating frequency, radiation pattern, polarization, or any combination of these characteristics [10,11].

Many antenna research groups studied reconfigurable antennas, Jin et al. [12] demonstrated WLAN and sub-6 GHz 5G applications, and a reconfigurable antenna with differential frequency was presented. These antennas can operate in single or dual-band modes depending on the switch state. To achieve reconfiguration, a lumped element switch is used. Ullah et al. [13] demonstrated a reconfigurable antenna with pattern reconfiguration for 5G sub-6 GHz bands that operate in three modes across multiple frequency bands (3.1, 3.8, and 4.1 GHz), X-Band Satellite (7.8 and 9.5 GHz), and WiFi (2.45 GHz). Four PIN diodes are used to execute frequency reconfiguration of the antenna, and two diodes are placed in the hexagon's radiating area. In contrast, the other two PIN diodes are connected to the

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ground's inverted L-shape and conventional coplanar waveguide.

Khan et al. [14] showed how defective ground construction affected several antenna parameters. A cavity-backed slot antenna reconfigured in terms of frequency, radiation pattern, and polarization was reported by Ge et al. [15]. Reconfigurability is achieved by electronically changing the state of switches between two crossed slots carved on the surfaces of a substrate-integrated waveguide cavity. For linear polarization states, tuning occurs between three frequency bands, and two frequency bands for circular polarization states. In another paper [16], a monopole frequency reconfigurable antenna was introduced. Reconfigurability is accomplished through the use of three-pin diodes. There are four different modes of operation. There are applications for each mode specifically. Global System for Mobile Mode 1 (GSM), 3G Advanced/Long Term Evolution Mode 2 (LTE), and WiFi, WLAN, and ISM applications operate in mode 3, whereas WLAN and airport surveillance radar band apps operate in mode 4. An antenna employs six separated frequency bands, including WiFi, WiMAX, UMTS, and WLAN, as presented by Shah et al. [17].

To the best of the authors' knowledge, few designs in the literature can reconfigure all three antenna features. Rodrigo et al. [18] used a tunable parasitic layer to achieve a reconfigurable antenna with frequency, polarization, and radiation pattern reconfiguration. The prototype comprises a patch antenna and a parasitic pixel surface with 66 pixels and 60 switches. The antenna can switch between four polarizations simultaneously, bend the radiation beam across 30° in two main planes, and tune its operating frequency over a 25% range. This design, however, has a huge antenna and a rather sophisticated DC biasing circuit. Another article [19] discusses a small, flexible, multiband planar inverted-F antenna. The antenna is designed for GPS, LTE, UWB, and satellite systems. Seven separate bands were obtained using a single radio frequency (RF) switch.

The proposed antenna has a promising gain, high radiation efficiency, and a small dimension. It is reconfigurable and radiates on various quad bands. The reconfiguration uses switches (pin-diode) and radiates in four different operating bands while maintaining good gain, radiation efficiency, and small size. The designed antenna has many advantages, including small size, low cost, lightweight, and easy fabrication. The main disadvantages of the design are interference, fading, multipath, and switch mismatching.

2 Antenna design

The suggested design configuration is shown in Figure 1. The design has dimensions 30 × 20 × 1.6 mm^3 on a substrate (FR-4) of thickness 1.6 mm. The design was simulated and optimized by using Computer Simulation Technology (CST). The dimensions of the design are $W1$ = 20 mm, $L1$ = 30 mm, $W2$ = 6 mm, $L2$ = 11 mm, $W3$ = 4 mm, $W4$ = 3.75 mm, $W5$ = 2.5 mm, $W6$ = 1 mm, $W7$ = 2 mm, $L3$ = 8 mm, $L4$ = 10 mm, $L5$ = 4.5 mm, $L6$ = 4.2 mm, and $L7$ = 2 mm.

To construct the reconfigurable antenna and obtain comparable test data, a PIN diode can be included. High-

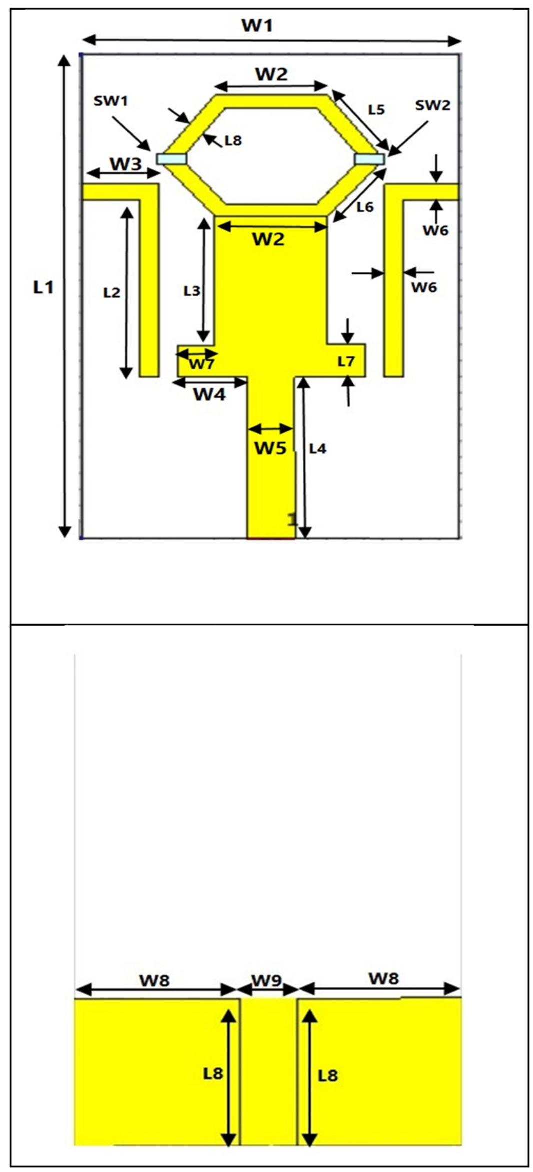

Figure 1: Top and Bottom view of the suggested antenna.

frequency return loss measurements were taken in a practical setting (2–6 GHz). For testing reasons, two pin diodes are used to accomplish the switching capabilities conditions, i.e., the Off and On states.

2.1 Technique of switching

Due to their similarity to variable resistors in the RF spectrum, two switches (pin diodes) are utilized for switching. The active resonant length of the antenna is changed by the open and short circuit behavior of these pin diodes, which causes the antenna's operating frequency to adjust. Figure 2 depicts the corresponding circuits for a pin diode switch on and Off states. It is simply R and L in series with a low value "R_L" and an inductor "L" for the state. In the Off state, it corresponds to an R, L, and C circuit, possessing inductor "L" in parallel with resistor "R_h" and a capacitor "C." In this work, a Skyworks SMP1345-079LF pin diode is used. According to its datasheet, CST has been used to simulate it as $R_L = 1.6\ \Omega$, $L = 0.75$ nH, and $C = 0.18$ pF.

2.2 Circular patch and field configuration

The circular patch antenna can be modified by making the ground plane, patch, and substantial between them as a circular cavity. Its radius is the single degree of freedom for regulating the antenna modes (Balanis, 1982). A cavity model makes it easy to analyze the antenna (Richards, 1988; Gonca, 2005). A cavity comprises two conductors, one at the top to represent the patch, and another at the bottom to represent the ground plane and a cylinder-shaped, ideal magnetic conductor wrapped around the cavity's surface. It is assumed that the dielectric substance of the substrate is stretched beyond the patch's size (Richards, 1988).

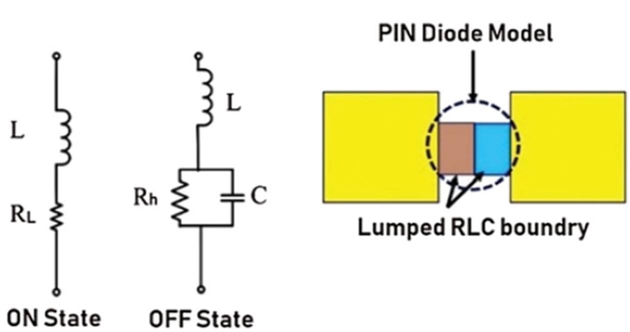

Figure 2: Equivalent circuits for a PIN diode's On state and Off state.

The vector potential can be used to determine the field configuration within the cavity. The homogeneous wave equation must be satisfied by the magnetic vector potential Az (Balanis, 1982)

$$k_\rho = \frac{X'_{mm}}{a}, \tag{1}$$

$$k_z = \frac{p\pi}{h}, \tag{2}$$

where m, n, and p are the integers as $m = 0,1,2, \ldots\ldots$, $n = 1,2,3, \ldots\ldots$, and $p = 0,1,2, \ldots\ldots$. The zeros of the derivative of the Bessel function $J_m\ (x)\ m$ are represented by X'_{mn}, and they determine the order of the resonant frequencies. The substrate height is very small for typical microstrip antennas, and the fields along z are constant ($p = 0$ and $k_z = 0$). As a result, the TM_{mn0} modes' resonant operating frequency can be written as

$$(f_r)_{mn0} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\left(\frac{X'_{mn}}{a}\right). \tag{3}$$

A circular patch's field can be calculated using the principle of Equivalence which an equivalent magnetic current density radiated in space replaces in the cavity's circumferential wall. Based on the cavity model and assuming a TMz_{110} mode field distribution below the patch, the cavity's perpendicular electric and magnetic fields for cosine angle fluctuations can be written.

2.3 Circular patch radius and effective radius

The patch radius is determined by treating the patch dimension as a circular loop using equation (4) (Balanis, 1982).

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi\varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{1/2}}, \tag{4}$$

$$F = \frac{8.791 \times 10^9}{f_r\sqrt{\varepsilon_r}}. \tag{5}$$

Equation (4) does not consider the fringing effect. Because it increases the patch's electric size, the active radius of a patch is given by (Balanis, 1982)

$$a_e = a\left\{1 + \frac{2h}{\pi\varepsilon_r a}\left[\ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{1/2}. \tag{6}$$

As a result, the dominant TMz_{110}'s resonant frequency is given by (Balanis, 1982)

Table 1: PIN diode conditions for different frequencies

Modes	SW1	SW2	Bands (GHz)	Pattern
1	Off	Off	4.6	*XY* plane
2	Off	On	2.7 and 4.8	*YZ* plane
2	On	Off	2.7 and 4.8	*YZ* plane
3	On	On	3.6	*XZ* plane

$$(f_r)_{110} = \frac{1.8412 v_0}{2\pi a_e \sqrt{\varepsilon_r}}. \quad (7)$$

Directivity

Directivity is one of the most crucial performance indicators of all antennas, as expressed by (Balanis, 1982)

$$D_0 = \frac{U_{max}}{U_0} = \frac{4\pi U_{max}}{P_{rad}}. \quad (8)$$

2.4 Resonant modes

The proposed design achieves frequency selectivity by changing each switch's state (On and Off states), exhibiting short and open circuit behavior among radiated patches.

The design has four operating modes, each with its own particular set of resonance frequencies. The antenna covers a 4.6 GHz band, Mode 1 (SW1 is Off and SW2 is Off). The design resonates at 2.7 and 4.8 GHz in Mode 2 (SW1 is On and SW2 is Off or SW1 is Off and SW2 is On) and the

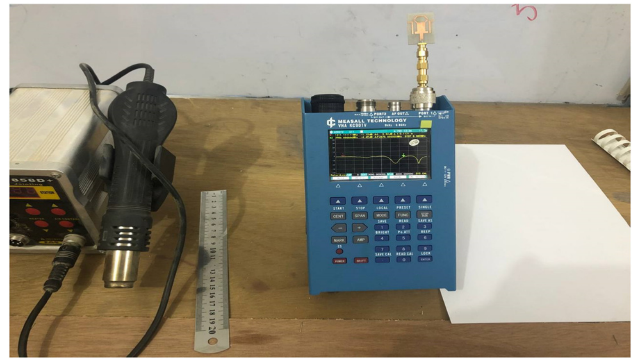

Figure 3: Mode 1 measurement setup for the proposed antenna's radiation pattern.

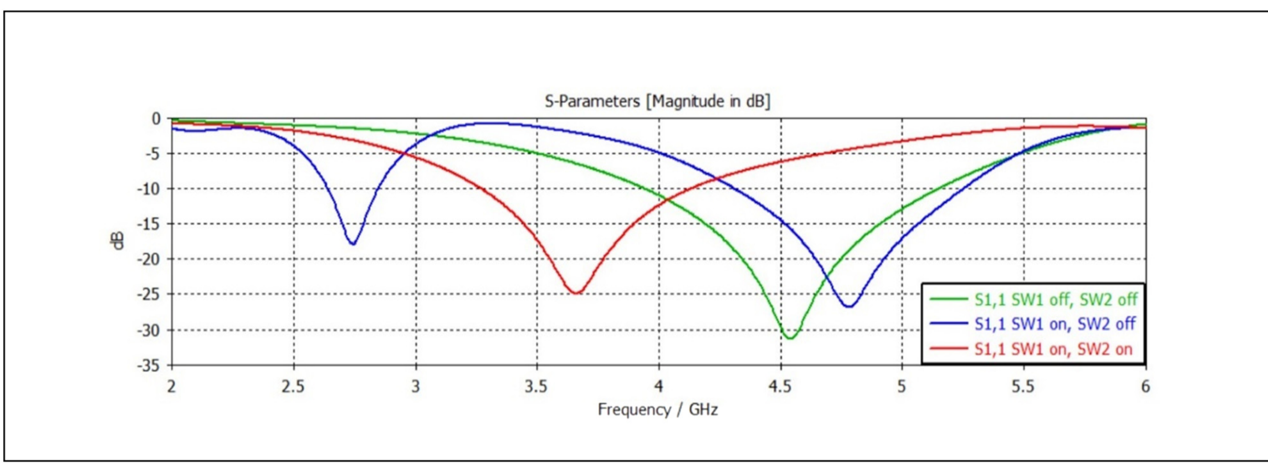

Figure 4: Return losses for all modes of operation.

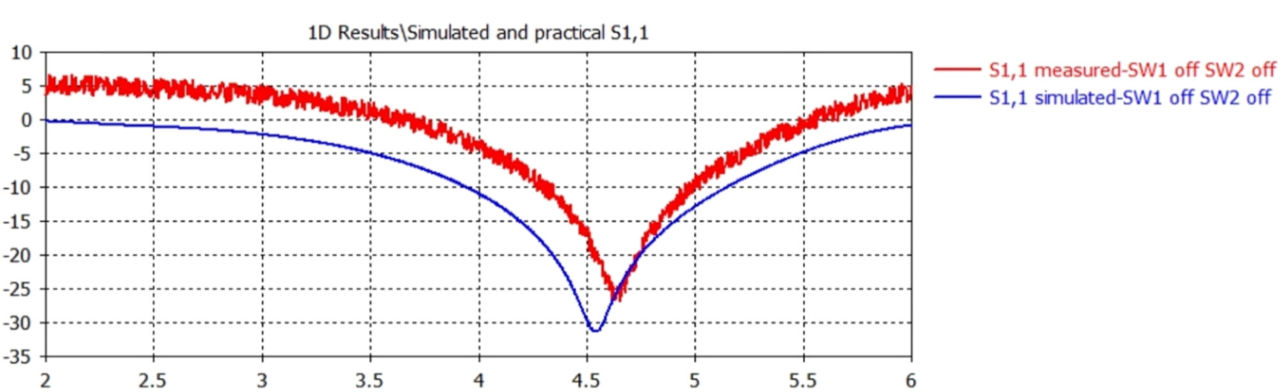

Figure 5: Mode 1 simulated return losses and measured return losses comparison. (SW1 = Off and SW2 = Off).

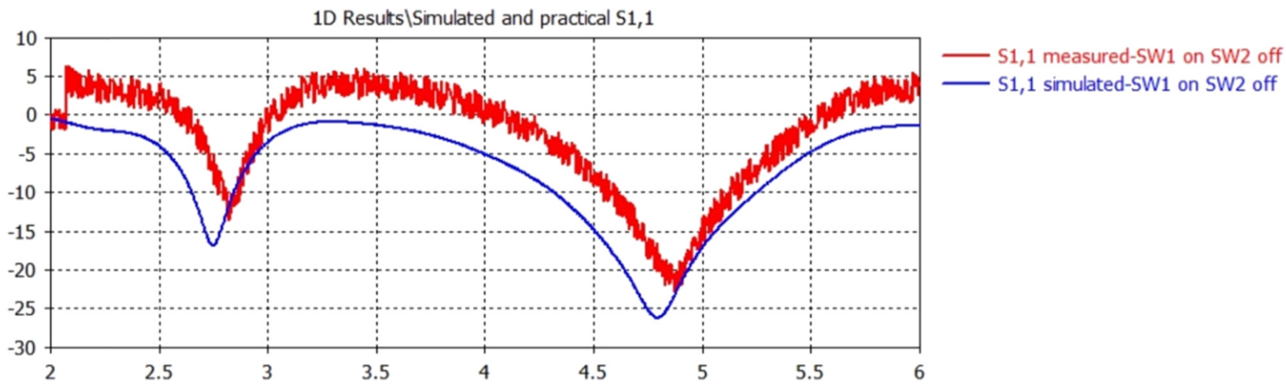

Figure 6: Mode 2 simulated return losses and measured return losses comparison. (SW1 is On and SW2 is Off or SW1 is Off and SW2 is On).

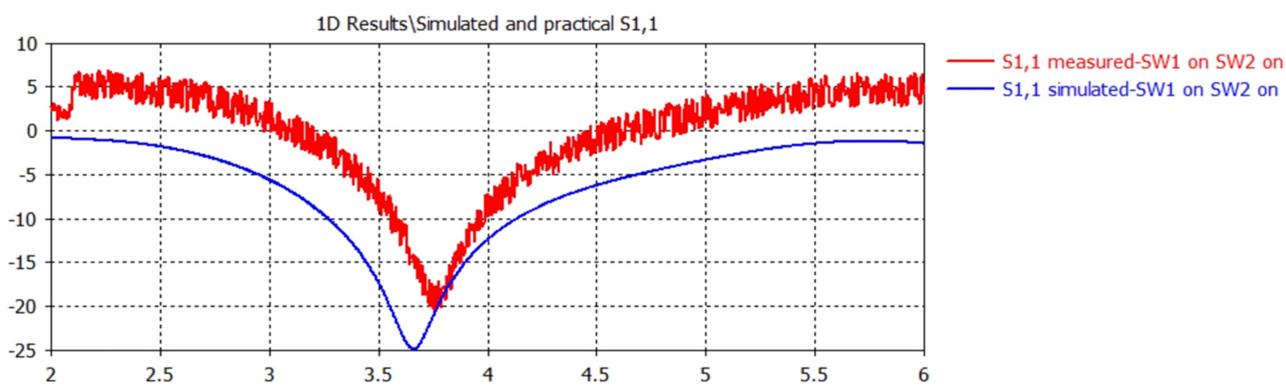

Figure 7: Mode 3 simulated return losses and measured return losses comparison (SW1 = On and SW2 = On).

design resonates at 3.6 GHz in Mode 3 (SW1 is On and SW2 is On). Table 1 details the pin diode conditions at each mode of operation and its resonant band.

3 Results and discussion

CST microwave studio (MWS) is used for designing and analyzing the proposed design, built on the material substrate (FR-4) with a relative permittivity of ε_r = 4.4, leading to smaller antenna dimensions 30 mm × 20 mm × 1.6 mm. The radiating structure is excited by a waveguide port with a standard size. The CST MWS' performance characteristics, including gain, return loss, and efficiency plots, are produced using the studio's typical conditions. In the vector network analyzer, the simulation results are validated experimentally. Figure 3 shows the experimental setup used to measure the design's radiated pattern in mode 1.

Table 2: Performance summary of the antenna

Model no.	Switches status	Operating frequency (GHz)	–10 dB BW (MHz)	Impedance matching (Ω)	Rad. efficiency (%)
Mode 1	SW1 = Off SW2 = Off	4.55	5,154–3,952(1,202)	50.63	90.8
Mode 2	SW1 = On SW2 = Off or	2.7–4.8	2,843–2,655 (187)	58	8086.75
	SW1 = Off SW2 = On		5,265–4,313 (952)	50.9	86.75
Mode 3	SW1 = On SW2 = On	3.67	4,138–3,272 (866)	50.46	92.6

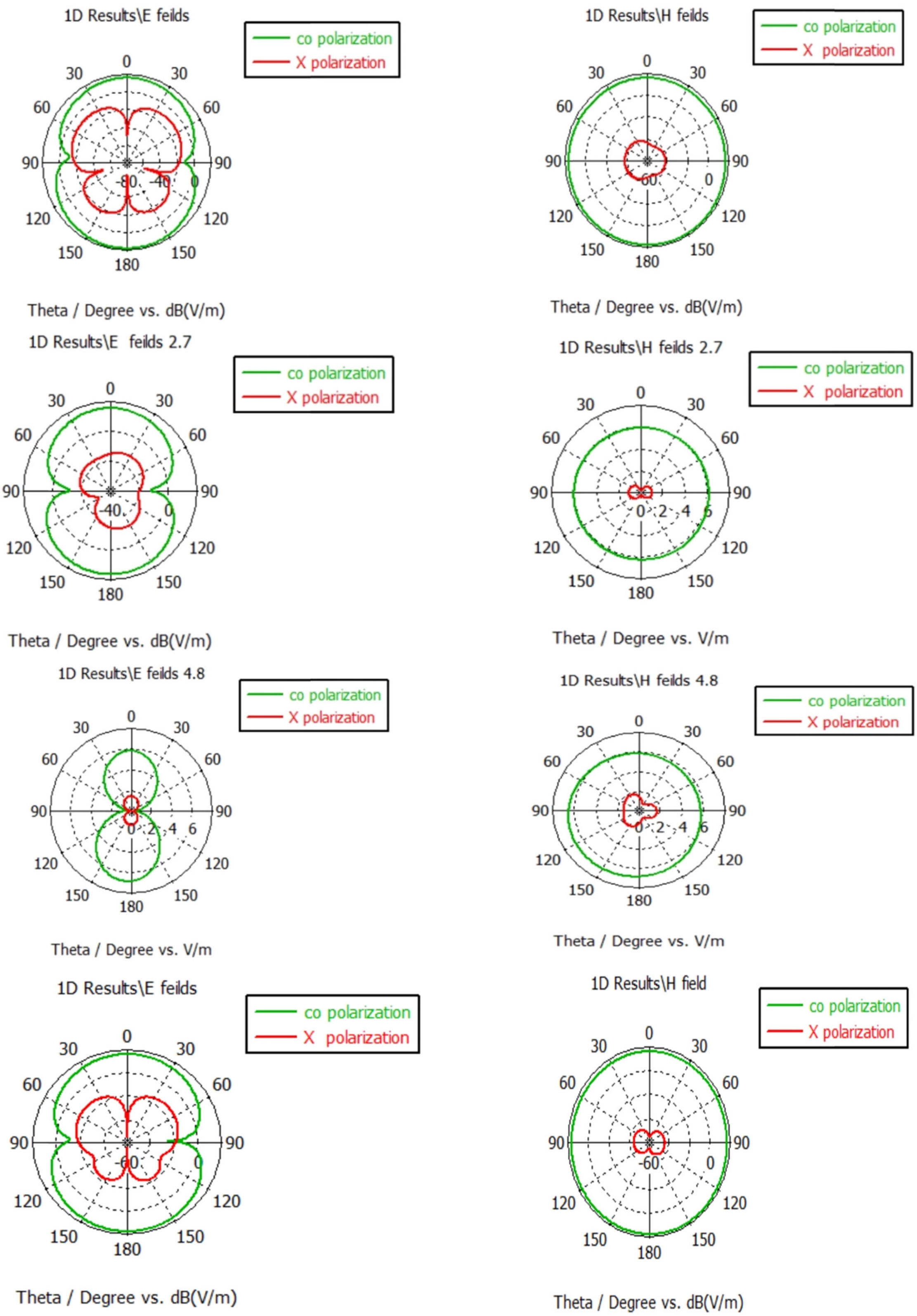

Figure 8: Co- and cross-polar radiation pattern.

Table 3: Comparison of the proposed design to previously published works

Ref.	Dimensions (mm^3)	No. of switches	Total no. of operation bands	Operating frequencies (GHz)	–10 dB BW (MHz)	Rad. efficiency (%)
[20]	40 × 35 × 1.6	1	3	2.45, 3.5, 5.4	490–1,360	76.4–86.5
[21]	60 × 60 × 1.6	3	5	2.4, 4.26, 4.32, 4.58, 5.76	1.31–2.77	—
[22]	53 × 35 × 1.6	1	3	2.45, 3.50, 5.20	147–1,820	85–90
[23]	39 × 37 × 1.6	1	3	2.4, 5.4, 3	550–1,220	>90
[24]	40 × 35 × 1.6	2	6	2.10, 2.40, 3.35, 3.50, 5.28, 5.97	335–1,220	92.5–97
[25]	37 × 35 × 1.6	2	4	2, 3.4, 2.4, 3.1	200–960	>85
[13]	30 × 20 × 1.6	4	5	3.1, 7.3, 2.24, 4.12, 9.12	410–1,880	80–85
This work	30 × 20 × 1.6	2	4	2.7, 3.6, 4.6, 4.8	188–1,202	80–92

3.1 Return loss and bandwidth (BW)

Figure 4 depicts the simulation of the return losses of all modes of the proposed design. Once both switches are Off (SW1 = Off and SW2 = Off), the proposed design operates in Mode 1, covering a frequency range of 4.6 GHz with a maximum return loss of 32.33 dB at the resonant frequency. The presented antenna resonates at two bands, 2.7 and 4.8 GHz, in Mode 2 (SW1 is On and SW2 is Off or SW1 is Off and SW2 is On), with a return loss of 18.17 dB at 2.7 GHz and 27.34 dB at 4.8 GHz. When both switches (SW1 is On, SW2 is On) are in Mode 3, the design operates at 3.6 GHz.

Figure 5 shows simulated and measured return losses for mode 1 (SW1 is Off, SW2 is Off). The evaluation shows a good degree of agreement between simulated and measured results.

Figure 6 shows simulated and measured return losses for mode 2 (SW1 is On and SW2 is Off or SW1is Off and SW2 is On). The evaluation shows a good degree of agreement between simulated and measured results.

Figure 7 shows simulated and measured return losses for mode 3 (SW1 is On and SW2 is On). The patch length has been increased. This is inversely proportional to the frequency, giving us a lower operating frequency, BW, and gain than other modes. The patch length has a minor effect on the resonant frequency, but it has a major effect on the BW, as illustrated in Table 2.

The evaluation shows a good degree of agreement between simulated and measured results.

3.2 Radiation pattern and radiation efficiency

Figure 8 depicts the co-polarization and cross-polarization radiated pattern simulation for the E-plane and H-plane. The result demonstrates the antenna radiation effectively in E- and H-planes in the co-polarization state. While the gain is primarily negative in cross-polarization, leading to very poor radiation in both primary planes (Table 3).

4 Conclusion and future work

A reconfigurable frequency antenna has been investigated that is controlled by two switches (PIN diode) incorporated into the structure through a 50 microstrip feed line. The effect of biasing lumped parts on antenna performance is demonstrated using the CST MWS simulator. The PIN diode status, On or Off, employed in this antenna can be altered to adjust the design's operating frequency and radiation pattern. Since it is cost-effective and low-profile, the proposed design can be used for various reconfigurable systems, including satellite and radar communication.

There are many suggestions for future works, such as redesigning the proposed reconfigurable antenna for pattern and polarization reconfigurability, redesigning the proposed antenna with another kind of substrate, and redesigning the ground of the proposed antenna material.

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Data availability statement: Most datasets generated and analyzed in this study are in this submitted manuscript.

The other datasets are available on reasonable request from the corresponding author with the attached information.

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