Low-profile frequency-reconfigurable antenna for 5G applications

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ABSTRACT

The demand for higher data rates has increased in recent years. The reconfigurable antenna that operates in the millimeter-wave spectrum (23.5 GHz – 29.64 GHz) was developed. This design is obtained by merging a half-circle radius of 3.97 mm, and a half-ring inner radius of 4 mm. The shape is similar to the round bottom flask. Two PIN diodes are used in this design to achieve frequency reconfigurability to meet the wideband mobile communication need of the future 5G. The suggested antenna, built on Roger RT5880 substrates and properties of $\varepsilon = 2.2$ and $\delta = 0.0009$, has been used as the antenna substrate. For all the resonant bands, the suggested antenna has a voltage standing waves ratio (VSWR) < 1.11. From 84 % to 92 %, the suggested structure radiation efficiency is calculated. A small antenna element has an excellent end-fire radiation pattern in the desired frequency bands. The antenna shows three reconfigurable bands, 25.17, 26.75, and 27.64 GHz, and gain (2.77−4.4) dBi. The suggested antenna is well suitable for future fifth-generation (5G) networks because of its notable features of small overall size (9.8×13×0.787) mm^3, wide bandwidth, and frequency reconfigurability.

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1. INTRODUCTION

Cell phones and other linked devices have generated exponential growth in mobile traffic, which has increased spectrum congestion for commercial mobile radio services [1]. Existing wireless communication technologies have been unable to fulfill the ever-increasing demands of end-users, especially for applications requiring data speeds on a Gbps scale [2]. Because of this issue, political and economic arguments have been made to sustain competition in mobile broadband services. Much work has been put into developing alternate solutions and tactics to alleviate the spectrum scarcity problem, including studying the millimeter wave spectrum or the extremely high-frequency band (EHF), which ranges in frequency from 30 GHz to 300 GHz [3]. High-speed multimedia data transmission and reception with more bandwidth are now possible because of current high-tech devices' widespread usage of wavelengths from 10 nm to 1 nm [4], [5].

The 5G of mobile technology is built on the foundation of millimeter waves, and it is envisaged that these waves will play a important role in mobile communication. Many businesses and economic sectors will use this technology because of its vast characteristics [6], [7]. For all of the ever-growing gadgets, 5G is intended to provide an enormous network foundation. Enhancing the user experience in many applications that need high data throughput and extremely low network latency [8]. However, some severe drawbacks of millimeter waves are their limited reach and responsiveness to atmospheric conditions and sensitivity to interference.

Thus, it will be a significant challenge for antenna experts to build antennas for future portable devices to operate in this frequency range [9], [10]. In addition, antennas with multi-tasking capabilities and strong radiation characteristics are urgently needed to maximize the advantages of this new area of the spectrum [11], [12]. When switching between multiple frequency bands, multiband and reconfigurable antennas have received the most attention. This way, one single reversible number of antennas may be replaced by a single antenna [13]-[17]. With their adaptability and good performance despite their tiny size and inexpensive cost, reconfigurable antennas are a breakthrough in telecommunications and wireless networks. Reconfigurable antennas are especially appealing because they may be dynamically altered by several antenna characteristics, including, radiation pattern, frequency and polarization, or by offering a compound reconfiguration consisting of altering multiple antenna parameters concurrently. Almost all reconfigurability is done through a method built into the antenna construction. Are used several active components, like microelectromechanical systems (MEMS) [18], PIN switches [19], [20], field-effect transistors (FET) [21], varactors [22], and optical switches [23]. It encourages the deliberate redistribution of radio frequency (RF). Currents throughout the antenna structure and reversible changes to its characteristics so that high antenna performance may be attained for varying applications and operating frequencies. The millimeter-wave spectrum is one of the best places to look for reconfigurability in a device. To allow mass production, microstrip patch antennas are widely employed for their advantages of being lightweight, small in size, inexpensive, strong, and easy to manufacture [24]. Different fractal forms have been utilized to build multiband antennas as part of the geometrical antenna design approach. The bandwidth is increased all around thanks to the wideband antenna. Ultra-wideband antennas have a wide range of characteristics that must be managed. During the design process, parameters such as frequency band and antenna are considered. Many ultra-wideband (UWB) antennas have been developed due to research into factors including gain, radiation patterns, and polarization [25], [26].

Reconfigurable antennas, particularly frequency reconfigurable antennas (FRAs), have been studied in many articles because of their potential to give a variety of operational resonant frequencies. Reconfigurable antennas, particularly FRAs, have been studied in many articles because of their potential to provide a variety of operating resonant frequencies. In [18] and [19], the pieces on the show discuss patch antennas for 5G millimeter-wave applications in the form of “Y” and “F” shapes, respectively. There are single and two-pin diodes in the radiating elements in these works that make it possible to change the frequency of the waves. All radiation properties have been reported. The first antenna covers three frequencies, while the second one covers two. After proper investigation, available literature suggests that it is still a challenge to create a millimeter wave reconfigurable antenna that can operate at several frequencies of the 5G technology while retaining high performance in terms of bandwidth, return loss, and all radiation properties.

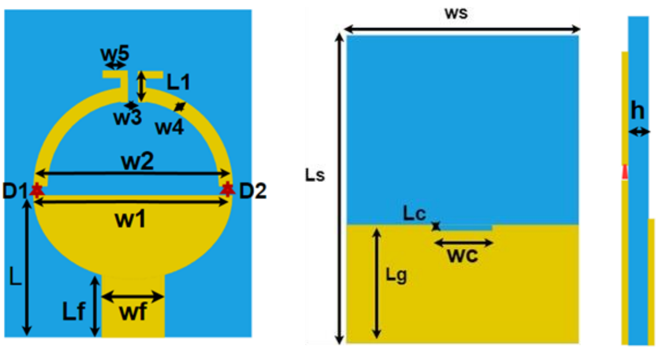
The suggested design has analyzed and studied a new still unique frequency reconfigurable patch antenna distinguished by its compact size. The antenna performance is investigated regarding the radiation pattern, reflection coefficient, bandwidth, and gain. The suggested antenna in this paper will be compared to corresponding works for the same frequency and application. The rest of the article is organized as: section 2 outlines the design technique and geometry of the proposed switchable multiband antenna. The simulated analysis described in sections 3 and 4 concludes this research work.

2. PROPOSED ANTENNA DESIGN

The antenna’s geometrical view is shown in Figure 1(a), Figure 1(b), and Figure 1(c) here. The suggested frequency reconfigurable multiband antenna’s radiating element obtained by merging a half circle radius of 3.97 mm, and a half ring inner radius of 4 mm, forms created. Cladding thickness of 0.035 mm by using copper. The Rogers RT 5880 substrate, with dimensions of (13×9.8×0.787) mm^3, a dielectric permittivity (εr) of 2.2, and a loss tangent (δ) of 0.0009, is utilized in the described design. An antenna that can change its frequency range is suggested in this section, which explains the antenna’s geometry and design theory. Table 1 shows the planned antenna’s dimensions in more detail.

Table 1. Shows the planned antenna’s dimensions

Parameters	Values (mm)	Parameters	Values (mm)
Ws	9.8	$W1$	7.94
Ls	13	$W2$	8
Lg	5	$W3$	1
Lf	3.2	$W4$	0.255
$L1$	1	$W5$	1.25
Lc	0.25	wf	2.5
wc	2.5	h	0.787



(a) (b) (c)

Figure 1. Geometry of the proposed reconfigurable 5G antenna: (a) top view, (b) bottom view, and (c) side view

2.1. Antenna designing

It is estimated that the copper ground plane employed covers 38.4% of the substrate surface (5×9.8) mm^2. For the proper impedance match, its dimensions are chosen. Figure 2 the steps depict the design procedures for the FRA. In the first step, a conventional monopole antenna was designed whose central frequency (f_r) of the circular monopole radiator can be estimated by the following (1) and (2), provided by [27]. Using a partial ground plane has resulted in improved efficiency and excellent outcomes in the distant field. Where:
b = the radius of the circular disk in cm
h = the height of the substrate in cm
ε_r = the relative dielectric constant of the substrate

$$b = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[Ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{0.5}} \quad (1)$$

f_r = the required resonance frequency

$$\mathrm{F} = \frac{8.791\times10^9}{\mathrm{f_r}\sqrt{\varepsilon_r}} \quad (2)$$

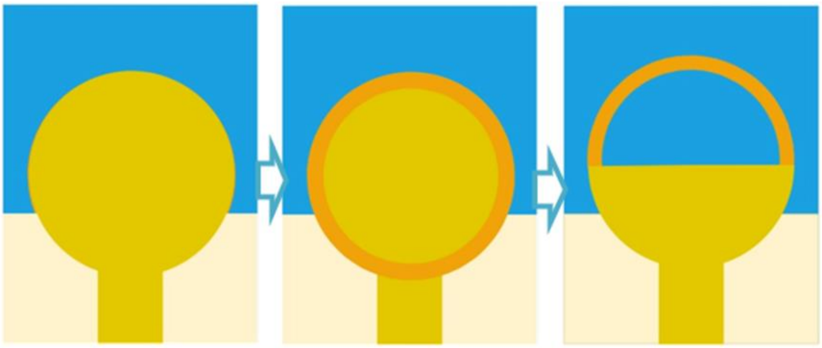


Figure 2. The appraisal of a proposed antenna involves several processes

Figure 3 shows the comparison of S-parameters between the conventional rectangular monopole and the modified triangular shaped monopole antenna and half-circular monopole. The conventional half-circular monopole shows a resonance at 25.5 GHz with a return loss of –31.9 dB, while the triangular antenna exhibits a resonance at 25.5 GHz with a return loss of –22.35 dB, and the rectangular antenna exhibits a resonance at 25.5 GHz with a return loss of –22.35 dB for $|S11| < -10$ dB. As illustrated in Figure 4(a), Figure 4(b), and Figure 4(c), we can see that the reflection coefficient and bandwidth have improved by cutting the slot in the ground plane.

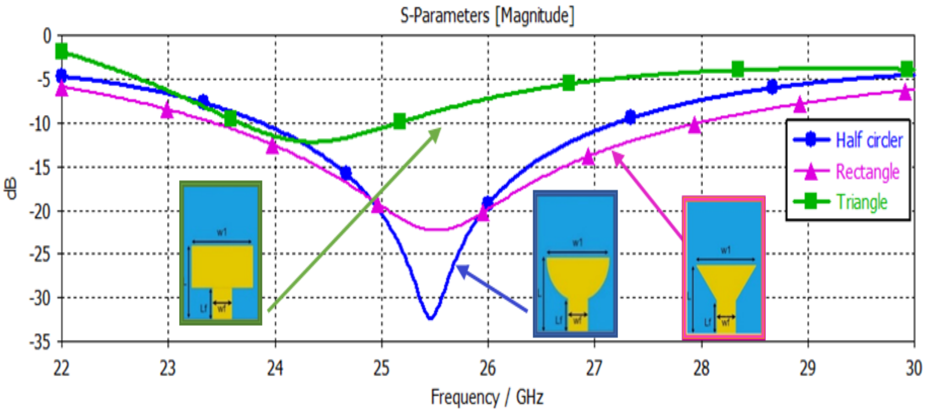
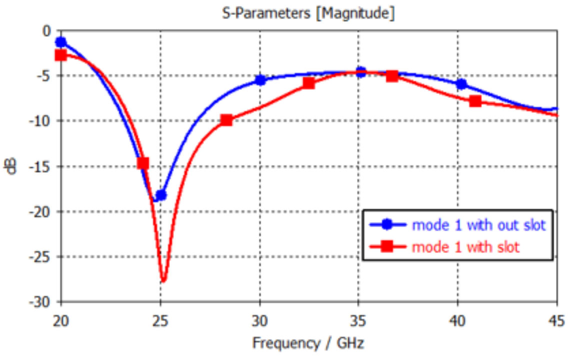
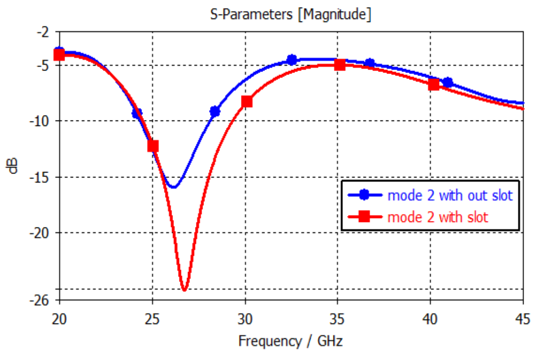


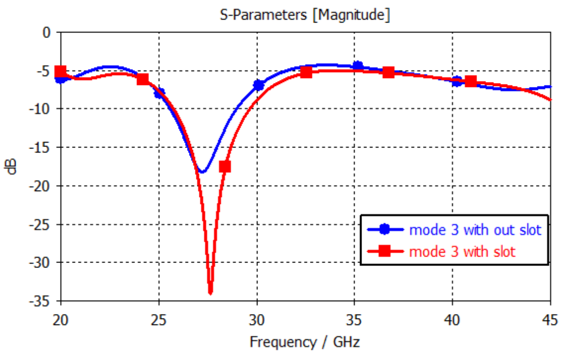
Figure 3. Simulated │S11│ of the rectangular monopole, triangular monopole, and half-circular monopole



(a)



(b)



(c)

Figure 4. Reflection coefficient for modes: (a) mode 1, (b) mode 2, and (c) mode 3

The resultant antenna shows single-band behaviors at every resonance. Finally, we added two PIN toggle switches (D 1 and D 2) to the radiating element, the PIN diode switches were inserted with a 0.7 mm gap between the patches as illustrated in Figure 1, to enable frequency reconfigurability. They hop between multiple frequencies using a single antenna. Analogous models of PIN diodes with 50 GHz maximum operating frequencies were employed in simulations. Three modes of operation may be achieved by inserting diodes into the antenna. Mode 1 is activated when both diodes are off, while the left diode is on and the right diode is off state, meaning mode 2, which is the same result when the left diode is off and the right diode on. On the other hand, the third mode occurs when both diodes are in an on state, representing mode 3.

2.2. Switching technique

A lumped element was used to represent the AlGaAs-Flip-Chip-PIN (PIN) diode with a 50 GHz most significant operating frequency. The diode is configured so that for the on state, it works as a series combination of 5.2 Ω resistor and 0.5 nH inductors. For the off state, it behaves like a series combination of 0.5 nH inductors with the parallel combination of 20×10^{-15} capacitor and 3 $K\Omega$ resistor. As displayed in Figure 5.

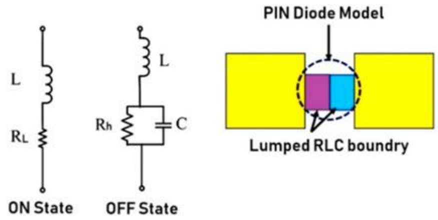


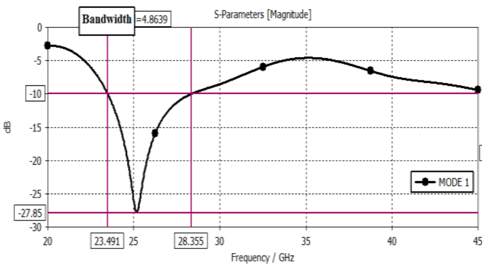
Figure 5. For both on and off states of operation, the PIN diode's corresponding circuits

3. RESULTS AND DISCUSSION

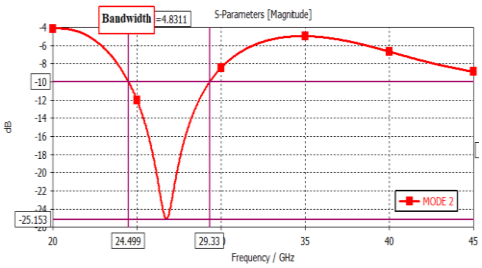
Computer simulation technology (CST) Microwave Studio MWS 2021 was used to build, model, and analyze the radiating structure. A waveguide port is used to power the proposed antenna. The CST Microwave Studio 2021 transient solver analyzes voltage standing wave ratio (VSWR), directivity, gain, far-field pattern, surface current distribution, and reflection coefficient under open-add-space boundary conditions.

3.1. Return loss and bandwidth

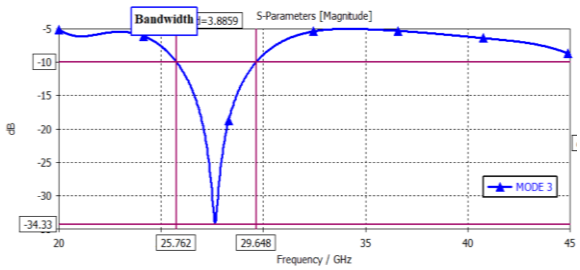
Figure 6 presents the resultant return loss of the different switching states of the diodes. It can be observed that all cases provide a single band. Figure 6(a) depicts a simulated bandwidth of 4860 MHz (23.5–28.36 GHz) that may be achieved when all switches (D 1 and D 2) are turned off, allowing the proposed antenna to operate in mode 1, with a frequency of 25.17 GHz with a return loss of -27.72 dB. And, with a frequency of 26.75 GHz, an antenna return loss of -25 dB, and a bandwidth of 4800 MHz (24.5–29.3 GHz), they are provided in mode 2 (when D 1 is on and D 2 is off), as shown in Figure 6(b). Switches D 1 and D 2 must be turned on for the antenna to function in mode 3 at 27.64 GHz with a return loss of -34 dB and 3880 MHz bandwidth (25.76–29.64 GHz) shown in Figure 6(c). A VSWR of less than 1.11 is found in all resonant bands, indicating that the antenna's driving point impedance is appropriately matched. In all working frequency ranges, the VSWR is less than 2, as illustrated in Figure 7.



(a)



(b)



(c)

Figure 6. S_{11} and bandwidth for various switching states of diodes: (a) mode 1, (b) mode 2, and (c) mode 3

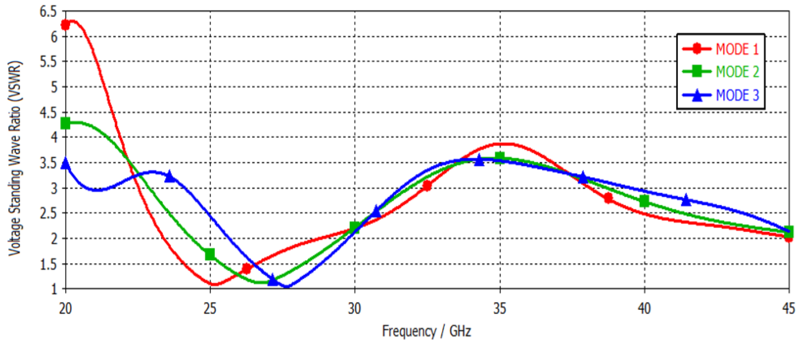
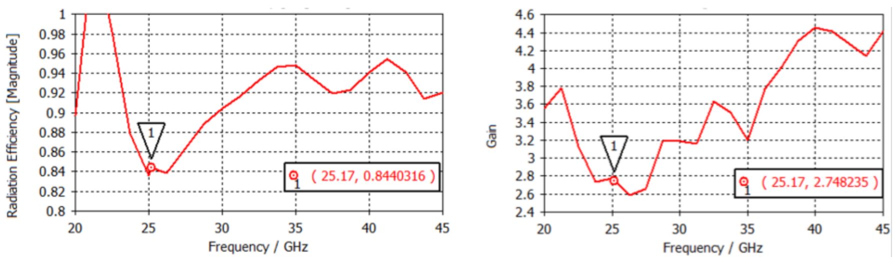


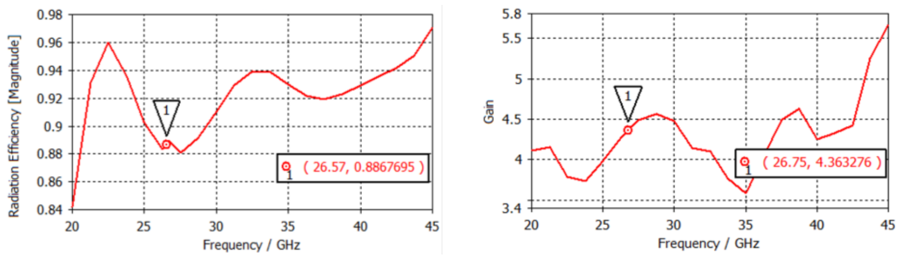
Figure 7. Shows the proposed antenna’s VSWR in various operating modes

3.2. Far-field radiation pattern

The antenna suggested in mode 1 operates at 25.17 GHz with a simulated peak gain and radiation efficiency of 2.77 dBi and 84%, respectively shown in Figure 8(a). In mode 2, with a gain of 4.4 dBi and radiation efficiency of 89% at 26.75 GHz shown in Figure 8(b). The antenna operates at 27.64 GHz in mode 3, with peak gains of 4.19 dBi and radiation efficiencies of 92% shown in Figure 8(c). The antenna’s simulated radiation pattern in the E-plane and H-plane depicted in Figure 9(a), Figure 9(b), and Figure 9(c), worked in frequency bands. Resonant frequencies are shown in three-dimensional gain plots to better understand the antenna’s radiation qualities in Figure 10(a), Figure 10(b), and Figure 10(c).



(a)



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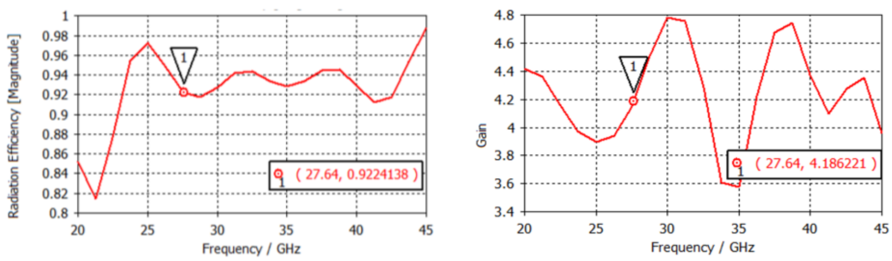
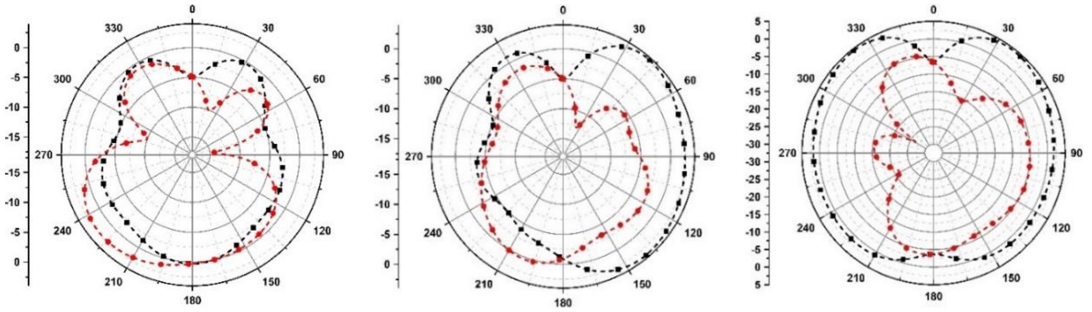


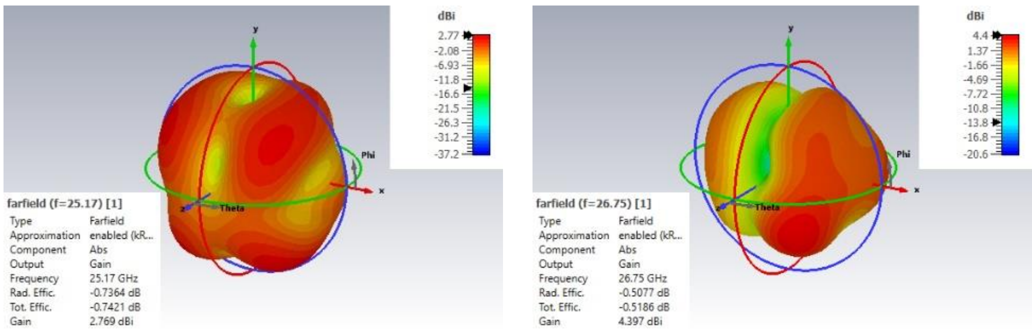
(c)

Figure 8. Shows the proposed antenna’s radiation efficiency and gain in various operating modes: (a) mode 1, (b) mode 2, and (c) mode 3

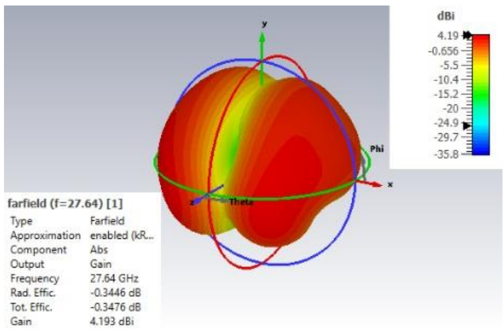


(a) (b) (c)

Figure 9. Analyses of the radiation pattern produced by the proposed antenna at various frequencies and switching states: (a) 25.17 GHz (mode 1), (b) 26.75GHz (mode 2), and (c) 27.64 GHz (mode 3)



(a) (b)

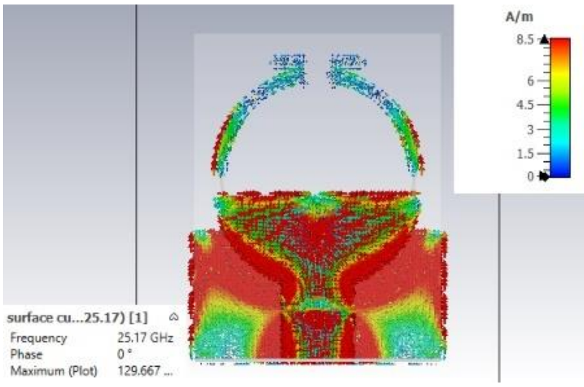


(c)

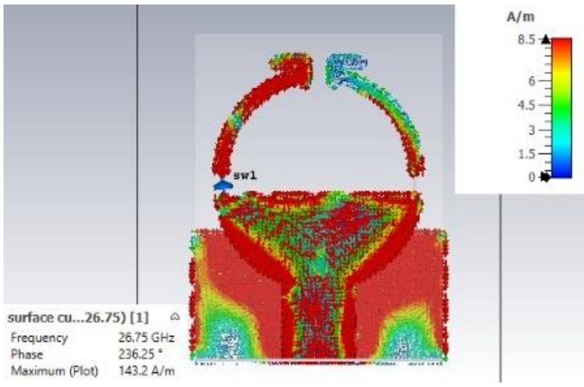
Figure 10. Three-dimensional gain patterns are shown on the graph at (a) 25.17 GHz (mode 1), (b) 26.75 GHz (mode 2), and (c) 27.64 GHz (mode 3)

3.3. Surface currents

Figure 11(a), Figure11(b), and Figure 11(c) shows distinct bands of the antenna radiating structure's surface current distribution. An antenna's surface currents may show how its operating modes alter them. In mode 1, the antenna works at a frequency of 25.17 GHz, and the primary radiator's surface current density is greater, contributing to 25.17 GHz radiation. A single-band operation (i.e., a frequency range of between 26.75 and 27.64 GHz) is possible in mode 2 and mode 3. In terms of surface currents, a larger section of the radiator contributes to the bottom band, whereas a smaller area contributes more to the top band. Metal radiators with a greater surface current density suggest emitting radiation in lower frequency ranges (i.e., 25.17 GHz). It is worth noting that the top radiation bands are produced by much smaller radiator pieces (27.64 GHz). These currents show that the length of each frequency's contributing resonance decreases with the rise in frequency to prove the inverse connection between frequency and length. Table 2 summarizes the performance of the proposed antennas.



(a)



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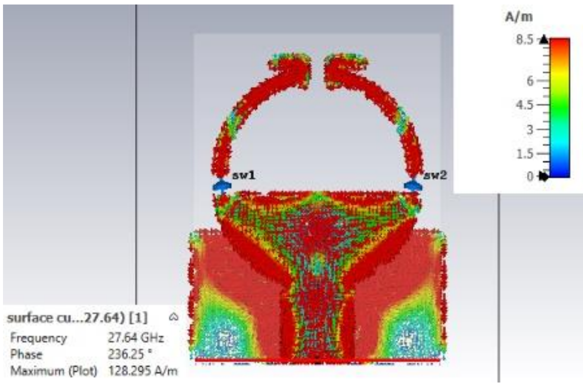

(c)

Figure 11. The proposed antenna's surface current in various modes: (a) 25.17 GHz (mode 1), (b) 26.75 GHz (mode 2), and (c) 27.64 GHz (mode 3)

Table 2. Summarizes the antenna's results

Mode on	Conditions	Operating frequency (GHz)	−10 dB B.W (MHz)	Gain (dBi)	S_{11}	Radiation efficiency (%)
1	Switches D 1 and D 2 turned off	25.17	23.5–28.36 (4860)	2.77	-27.7	84
2	When D 1 is on	26.75	24.5–29.3 (4800)	4.4	-25	89
3	When D 1 and D 2 is on	27.64	25.76–29.64 (3880)	4.19	-34	92

The proposed antenna performance is compared to some related works dedicated to millimeter-wave 5G applications in Table 3. After analyzing the results reported in this table, we can deduce that the suggested antenna is more compact than the existing antennas mentioned in [28]-[30] and has better gain than the work reported in [28], [30], [31], and has better radiation efficiency than the work reported in [29], [31] suggested antenna to operate on three different frequency bands, which is more than the number of bands achieved in [29], [31]. Compared to other potential antennas, the most notable difference is that the suggested antenna can function over three different frequency bands, which is more compact than any other antenna except [31].

Table 3. Compared to earlier recorded results, the suggested antenna

Ref no	Dimension (mm^2)	Provider frequencies	S_{11} dB	Gain dBi	Radiation efficiency %
[28]	690	26, 27, 28	-42, -18, -23	1–4	97–98
[29]	201.55	27.95, 28.65	-17.5, -22	6.43, 6.13	nil
[30]	144	26, 27, 28, 29	-20, -23, -21, -18	3.4–3.7	78–97
[31]	99	28, 38	-38, -48	2.62, 4.39	>70
This work	127.4	25.17, 26.75, 27.64	-27.7, -25, -34	2.77–4.4	84–92

4. CONCLUSION

This study presents the design and simulation results of frequency reconfigurable antenna (FRA). The two pin diodes switches change the configuration of the reposed antenna for 5G millimeter wave applications. The antenna consists of a one-half circle and one-half ring of that radius, 3.97 mm and 4 mm, respectively, forms created connected or disconnected through diodes. It is possible to reconfigure the frequency band by using the three distinct states of the diodes in accordance with the needs of the system. It is possible to reconfigure the frequency band by using the three distinct states of the diodes in accordance with the needs of the system. The antenna is small and has three reconfigurable bands, making it appealing performance in terms of bandwidth, return loss, and stable gain characteristics. Because the suggested antenna's bandwidth for all modes ranges from (23.5 GHz – 29.65 GHz), this is the desired bandwidth for 5G mm-wave applications.

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