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Research Article

Design and analysis of a frequency reconfigurable hybrid fractal microstrip antenna with modified patch and ground plane for millimeter wave energy harvesting applications

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ABSTRACT

The rapid expansion of fifth-generation wireless systems and Internet of Things technologies has created a strong demand for energy-efficient and autonomous wireless devices. A key challenge in this domain is the design of compact and high-performance antennas capable of supporting millimeter-wave operation while enabling efficient radio frequency energy harvesting. In this work, a frequency-reconfigurable hybrid fractal microstrip antenna integrated with a defected ground structure is proposed to address these challenges. The antenna is reconfigurable at two different frequencies (29 GHz and 33 GHz) through the use of two PIN diodes, dynamically switching between multiple operating modes. The design is simulated using a full-wave electromagnetic solver, and experimentally verified with a fabricated prototype on a Rogers RT/duroid 5880 substrate. The proposed antenna exhibits a maximum achieved gain of 9.8 dBi in simulation and 9.12 dBi in measurement with high radiation efficiency of about 94%. It also shows wideband performance (25–35 GHz) and excellent polarization isolation (above 30 dB) in the reconfigurable mode. The obtained results are in a good agreement with simulations with small differences due to manufacturing and measurement tolerances. The novelty of this work is the synergistic integration of hybrid fractal geometry, defected ground structure and frequency reconfigurability based on PIN-diode in a single compact antenna offering higher gain, efficiency and operational flexibility over existing designs. The obtained results show that the proposed antenna is a potential candidate for integration into radio frequency energy harvesting systems and adaptive millimeter wave communication applications, which supports the development of next generation energy-autonomous wireless devices. The proposed antenna is suitable for integration into energy autonomous Internet of Things devices and adaptive fifth-generation wireless systems, enabling practical deployment in real-world scenarios.

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INTRODUCTION

The last decade has seen rapid growth in wireless communication systems due to the rise in mobile data traffic, high-definition multimedia services, and Internet of Things (IoT) devices. The telecommunications industry has moved to the fifth-generation (5G) and beyond-5G (B5G) technologies as the fourth-generation (4G) and Long-Term Evolution (LTE) networks are reaching their capacity limits. These new networks will allow massive machine-type communications (mMTC), ultra-reliable low latency communications (URLLC) and enhanced mobile broadband (eMBB). This enables applications such as autonomous vehicles, augmented reality, intelligent healthcare and large sensor networks [1].

The research has moved toward the millimeter-wave (mmWave) spectrum, more specifically the Ka-band (26–40 GHz), to satisfy the rising demand for higher data rates and bandwidth. The Ka-band can support data rates up to a gigabit per second [2,3] due to its much larger bandwidth than frequencies below 6 GHz. However, mmWave propagation suffers from many problems like high path loss, absorption by atmosphere, rain attenuation and obstacles in the path of the signal [4]. These limits require that antenna systems should have high efficiency, high gain, stable radiation patterns and better radiation efficiency. MPAs are attractive in mmWave applications because of their low profile, light weight, ease of fabrication and compatibility with monolithic microwave integrated circuits (MMICs) [5]. These are good things but normal MPAs are not effective in wideband 5G systems because of their narrow bandwidth and low gain [6]. To overcome these limitations, several techniques for performance enhancement have been explored, including slot loading, stacked configurations and fractal geometries.

The designs of fractal antennas are of great interest because of their space filling properties and self-similar structures which increase the effective electrical length without increasing the physical footprint [7, 8]. With this you can miniaturize your antennas and operate on several bands. Hybrid fractal geometries are used to enhance the performance by combining various fractal patterns to enhance the current distribution, increase the higher order resonances and improve the polarization characteristics [9, 10]. You can change the radiating patch. You can change the ground plane to make it work better.

In Defected Ground Structures (DGS) the ground plane is intentionally disrupted. This alters the current flow on the surface and introduces inductive-capacitive (LC) properties [11]. If DGS configurations are properly designed, they can make the impedance bandwidth wider, reduce the quality factor (Q-factor), get rid of undesired harmonics and improve radiation efficiency [12]. Also, DGS methods can be used to reduce mutual coupling for small multi-element systems, which is critical to accommodate a multitude of 5G devices in a small area [13].

Today's wireless environments require antenna systems that work over a large range of frequencies. Static antennas aren't always the best in environments with spectrum changes. This problem is solved by frequency reconfigurable antennas that enable you to change the operating frequency in real-time by use of switching elements such as PIN diodes, varactors, or MEMS switches [14-16]. Reconfigurable antennas are useful as 5G systems require antennas to change the spectrum and manage beams on the fly.

Due to the increasing number of IoT sensor nodes, there is a great need for devices that can run on their own power at the same time. In large IoT networks, it is often not possible to change or recharge batteries, especially in places that are hard to reach or harsh. A promising solution is Radio Frequency Energy Harvesting (RFEH), which captures electromagnetic energy from the environment and converts it into usable DC power [17]. 5G mmWave networks carry a lot of data, which can be used as a source of energy for low-power IoT devices [18]. However, it is difficult to achieve good performance for small antennas in mmWave frequencies, due to dielectric losses, conductor losses and tolerances in the manufacturing process [19]. A self-sustained IoT sensor node powered by a millimeter-wave antenna for RF energy harvesting is illustrated in Figure 1.

Existing work presents the tradeoff antennas which are either compact but narrow band or wideband but physically bulky. There is a need of research to be carried out to effectively synergizes hybrid fractal geometries with advanced defected ground structure techniques to achieve a high gain, compact, and efficient radiator specifically optimized for Ka-bands and millimeter wave frequencies. Addressing this gap, this paper proposes the design and comprehensive analysis of a Frequency-Reconfigurable Hybrid Fractal Microstrip Antenna with a Modified Patch and Ground Plane. By combining the novel fractal geometry with optimized defected ground structure, the proposed design achieves multiple band resonance suitable for both 5G and millimeter wave energy harvesting for IOT low power devices. Rigorous simulation is used to verify the structure, which indicates a higher bandwidth, gain and efficiency compared to conventional topologies [20].

The principal contributions of this study are encapsulated as follows:

(i) New Hybrid Design Approach: The new hybrid design is proposed for the ka-band millimeter wave applications by combining the fractal geometry and defected ground structure. The proposed method exploits the synergistic interaction of these techniques to greatly improve the current distribution, the impedance matching and the radiation performance. This is different from previous works that used these techniques separately.

(ii) Frequency Reconfigurability using Dual PIN Diodes: A reconfigurable mechanism based on dual PIN diodes is used to switch between 29 GHz and 33 GHz on the fly. This makes it possible for the antenna to work on multiple bands, which is useful for both 5G communication

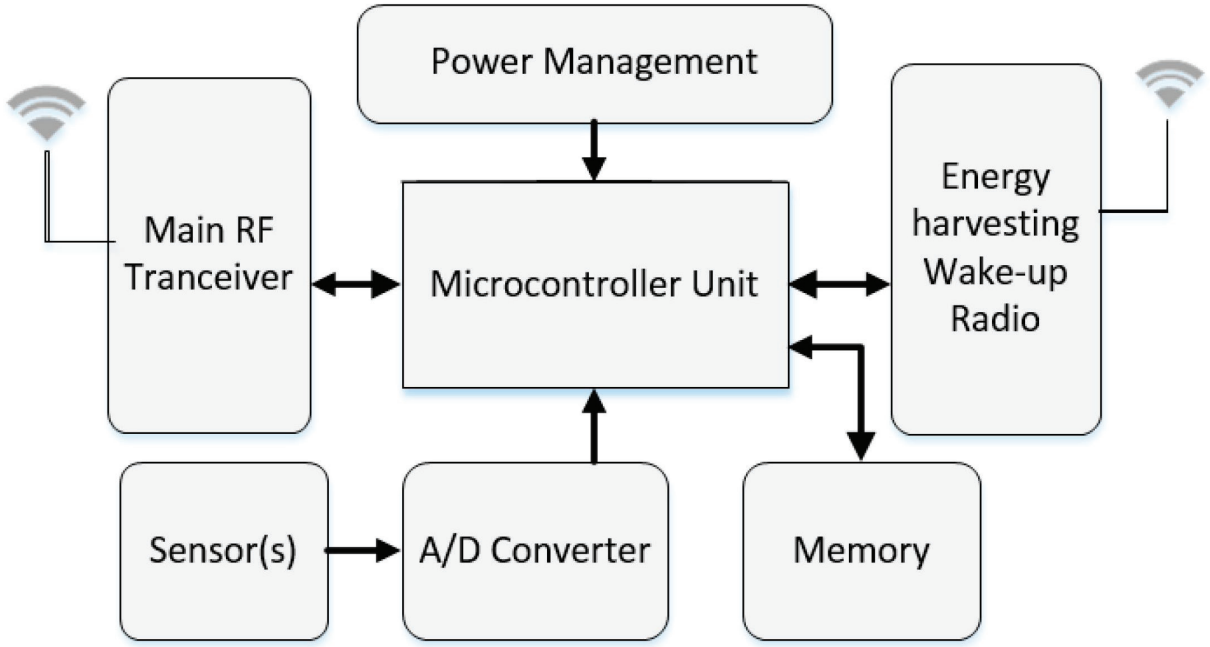


Figure 1. Block diagram of an RF energy harvesting-enabled IoT sensor node architecture.

and RF energy harvesting. This is not something that is often reported in compact fractal-based millimetre wave antennas.

(iii) Energy Harvesting-Oriented Aperture Design: The proposed design uses a larger aperture (50 × 70 mm) on purpose to maximise captured RF power. This particularly suitable for energy harvesting applications where the power received is of paramount importance.

(iv) High Performance Measurements: The proposed antenna has a high gain of about 9.8 dBi and radiation efficiency of about 94%. This indicates it is 15–30% more efficient and up to 2 dB more powerful than many existing designs.

(v) Compact Single-Element Structure without Arrays: This antenna uses a single element, which simplifies the design, reduces costs, and eliminates the losses associated with the feeding network in array-based rectenna systems. It is still working well. These contributions altogether demonstrate the proposed antenna as a high-efficiency, reconfigurable and application-driven solution for 5G systems and next-generation millimeter wave energy harvesting.

The proposed antenna is very useful in many new applications of the conventional communication systems. The rapid growth of the number of low-power Internet of Things (IoT) devices also increases the need of energy-autonomous sensor nodes that can be used in hard-to-reach places.

The proposed antenna with high gain, high radiation efficiency and frequency changing ability is a good candidate for radio frequency (RF) energy harvesting systems. These systems can harness ambient electromagnetic signals as a long-term power source. The antenna can also be used in fifth-generation (5G) wireless systems for adaptive communication, where dynamic frequency selection is needed to maintain stable connections even when the channel conditions change. Its small single element design makes it ideal for embedded systems, wearable electronics and environmental monitoring applications. This implies its application in both the field of communication and energy harvesting. Similar trends can also be observed in larger engineering systems where improvements in efficiency and optimization are still major problems.

Many of the reported designs are small at the expense of gain and efficiency, or use complicated and large array configurations to achieve high performance. Furthermore, the main techniques including fractal geometry, defective ground structure (DGS) and frequency reconfiguration are generally studied separately and few works present the use of these techniques together in a single design.

These problems require us to develop a small, high efficiency and flexible antenna, which can improve the performance by using many different methods but keep the structure simple enough to be used in real life. This is in line with recent trends in optimizing engineering and designing energy-efficient systems].

This work proposes a frequency-reconfigurable hybrid fractal microstrip antenna integrated with a defected ground structure to tackle these challenges. The design uses two PIN diodes to allow for dynamic switching between 29 GHz and 33 GHz. Here we combine the benefits of fractal geometry (making things smaller and being able to work on multiple bands), DGS (increasing bandwidth and efficiency), and reconfigurability (adaptive operation). The proposed work is

new in that it combines these techniques in a single element antenna which provides high gain (up to 9.8 dBi), high radiation efficiency (around 94%) and a lot of operational flexibility. This solves the main problems of the current designs.

Different approaches to improve the performance of millimeter-wave antennas for fifth generation applications have been investigated in recent works. Fractal-based antenna designs have been studied a lot for their potential to provide miniaturization and multiband functionality. For example, Sierpinski and Hilbert fractal geometries have shown that they can be compact but have generally low gain and narrow bandwidth.

The bandwidth has been improved by hybrid fractal methods, but there are still problems such as high cross polarization and complex structures. Defected ground structures have also been used for improving radiation and impedance bandwidth. These methods can improve things, but can also cause more back radiation or lower efficiency if not carefully optimized. Frequency-reconfigurable antennas using PIN diodes, varactors or microelectromechanical systems have also been proposed to help fifth-generation systems to make better use of the spectrum. But these designs usually have complicated biasing networks or higher insertion losses.

While these methods have shown promise on their own, there hasn't been much research on using fractal geometry, defected ground structures, and frequency reconfigurability together in a single design, especially for radio frequency energy harvesting applications at millimeter-wave frequencies. So, there is a clear need for a simpler and more effective antenna design that combines these methods to get high gain, high efficiency, and operational flexibility while keeping the structure small. The proposed work meets this need by creating a single antenna design that uses hybrid fractal geometry, defected ground structure, and PIN-diode-based reconfigurability to work well for both communication and energy harvesting.

Literature Survey

While the Introduction provides a concise overview of recent advancements, this section presents a more detailed review of state-of-the-art techniques in fractal antennas, frequency reconfigurability, and defected ground structures. In recent electromagnetic research the development of millimeter-wave antennas for 5G and energy harvesting applications have been remarkable expanded and in this section, we will review the state-of-the-art in fractal geometries, frequency Reconfigurability, and defected ground structures, highlighting the limitations of existing designs that the proposed work addresses.

Fractal Antennas for Millimeter-Wave Applications

Fractal geometry has been the most efficient way and widely used for trade-offs between the antenna size and the bandwidth. The antenna posses' enhanced bandwidth with compact in size, as it is suitable for majority of applications where the compactness is most important. In Sharma and Yadav [21], the authors proposed a Sierpinski carpet fractal antenna for 28 GHz applications, where the design has achieved a 12% size reduction, but compromises on the gain which was limited to 4.5 dBi, which is insufficient for long-range millimeter wave links. A hybrid Minkowski fractal approach was explored in Zhang et al. [22], which focused on the increase of gain and bandwidth for a potential operating frequency of around 38GHz.

Although the antenna possesses enhanced characteristics with around 14%, but the cross-polarization levels remained very much high due to the asymmetry of the fractal iterations. Latest advancements have majorly focused on high-order fractal iterations such that they exhibit miniaturization in the antenna size, and one of the author in Gupta and Pattnaik [23] has demonstrated with the use of 3rd- order Hilbert curve antenna which provides good stability and miniature structure but compromised on the bandwidth, where achieved less than 500MHz at the resonating frequencies. To overcome these limitations, Kim et al. [24] integrated a fractal patch with a metal material substrate due to which the bandwidth was significantly increases as well as the gain is boosted upto 3dB, but compromised on the profile height which was increased by a ratio of 5mm. Furthermore, Singh and Basu [25] investigated the novel idea of using bio-inspired fractal geometry for Ka band applications, where te peak efficiency was increased up to 885yet the design had a drawback of necessary dual band, which was required to uplink and downlink simultaneously.

Frequency-Reconfigurable Antennas in Millimeter-Wave Systems

In order to deal with dynamic spectrum allocation in 5G environment, it becomes very essential that the frequency Reconfigurability is achieved such that the antenna features can be enhanced and utilization ration increases. In Park and Lee [26], a PIN diode based reconfigurable antenna was proposed for operating frequency ranging from 28GHz to 38GHz where active biasing network was used to enhance the antenna, but at the same time there was a significant increase in the insertion loss and complexity. Similarly in Ivanov et al. [27], authors proposed varactor-tuned patch antenna such that the tuning can be carried out in the frequency ranging 26 to 30 GHz. However, the property of non-linearity of varactors at millimeter wave frequencies have resulted in the signal distortion at higher power levels.

Along with the traditional study, there was also focus on alternative reconfiguration mechanisms where the Reconfigurability was achieved by using fluid-based antenna where the liquid metal channels were presented in Wu [28], offering wide tuning ranges, but the drawback was the switching speeds where not matching with the required modern 5G protocols. In contrast to that Ali [29] utilizes the switching by using MEMS switches as they achieved high-isolation reconfiguration between24 GHz and 28 GHz. The antenna possesses high performance, but limiting at commercial deployment due to the fabrication cost as well as the fragility of MEMS. A simpler approach using

shorting pins to modify the dominant mode was demonstrated in Chen and Li [30] where the antenna provided discrete tuning steps rather than desire flexibility.

Defected Ground Structures to Enhance Bandwidth

Now the focus is shifted to defected ground structure where many researchers have shown interest to understand the impact on the antenna performance. In Al-Saedi et al. [31], a dumbbell-shaped defected ground structure was employed and the author states that the use of the said shape can suppress higher-order harmonics in a resonating frequency of30 GHz for the proposed patch antenna. The design enhanced the performance and was able to successfully use the entire proposed spectrum but compromised on the front to back ration. Similarly in Paracha et al. [32], a U-slot defected ground structure configuration was studied specifically for enhancing the bandwidth, due to which the fractal antenna provides a 8% increase in the bandwidth in the frequency ranging up to 35Ghz. However, as it had a large slot size, which produces the back radiation significantly high, the antenna was not suitable for on-body or integrated applications. In recent times more complex defected ground structure patterns have merged in the field of compact and miniature applications, Islam [33] proposed one of its kind, a spiral-shaped defected ground structure to use under millimeter wave and the antenna potentially reduced its dimensions by 20%, but at the same time the antenna efficiency dropped down to 75% due to factors such as leakage currents. A comprehensive study was also undertaken where the author in Das and Mitra [34] presented a comparison between various defected ground structure shapes for Ka-band applications, in which there was significant impact on the antenna when a hybrid model is used instead of a traditional model. The antennas achieved good bandwidth and cross-polarization. Along with this even a study emerged in which the author in Liu [35] introduced a "floating" ground plane concept with better efficiency; the only difficulty was that the manufacturing with PCB process was very difficult to achieve.

Millimeter-Wave Energy Harvesting (RFEH) Systems

We now focus on the crucial part of the proposed paper, the feasibility of gathering the energy from millimeter wave signals, The author in Parchin [36] proposed a high-gain rectenna array operating at 28 GHz which has achieved an efficiency of 45% but as the antenna designed using large arrays, it was impractical to use in the compact IoT nodes. Similarly in Ahmed and Alsharif [37], a dual band energy harvesting system was proposed in the vast range for frequencies which are from 24GHz to 60 GHz, and the matching is carried out for the lower and upper bands, as the same matching network was used, which leads toward the poor efficiency at upper band. Latest works have been focused on wideband harvesting for IoT applications under Ka-band, and the author in Zhou [38] demonstrated the use of tapered slot antenna capable of harvesting the RF energy in the frequency range of 26–40 GHz, the only drawback is that the end-fire radiation pattern is less suitable for planar mounting on device surfaces. In another research work carried out by Roy [39], discussed about the ambient harvesting on the node, but lacked the directive gain to capture weak signals. Finally, the authors in Huang and Lin [40] highlighted the need of reconfigurable antennas to track the resonance frequency for strongest available 5G beam, this capability remains largely unexplored in the current literature. Table 1 provides the comparison of the proposed antenna over the existing work carried out.

Table 1. Comparison of Proposed Antenna with existing works

Ref	Year	Antenna Geometry	Operating Freq. (GHz)	Technique Used	Performance / Limitation
Sharma and Yadav [21]	2023	Sierpinski Carpet Fractal	28	Fractal Miniaturization	Compact size, but low gain (4.5 dBi).
Zhang et al. [22]	2024	Hybrid Minkowski Patch	38	Hybrid Fractal	Improved bandwidth, but high cross-polarization.
Gupta and Pattnaik [23]	2024	3rd Order Hilbert Curve	5G Band	High-Order Fractal	Good miniaturization, but very narrow bandwidth (<500 MHz).
Kim et al. [24]	2023	Metamaterial Loaded	28	Metamaterial Superstrate	High gain, but large profile height (>5 mm).
Park and Lee [26]	2024	PIN-Diode Reconfigurable	28 / 38	Active Switching	Dual-band, but complex biasing network and high insertion loss.
Al-Saedi et al. [31]	2023	Rectangular Patch	30	Dumbbell defected ground structure	Harmonic suppression, but reduced Front-to-Back Ratio (FBR).
Paracha et al. [32]	2024	Patch with U-Slot	35	U-Slot defected ground structure	Wide bandwidth (8%), but excessive back radiation.
Ahmed and Alsharif [37]	2023	Dual-Band Harvester	24 / 60	Standard Patch	Large frequency separation makes matching network difficult.
This Work	2025	Hybrid Fractal + Slot	29 / 33	Fractal + defected ground structure	Compact, Dual-Band, High Efficiency (>90%), High FBR.

ANTENNA DESIGN AND CONFIGURATION

This part talks about how the proposed hybrid fractal microstrip antenna was designed, how it is built, and how its parts can be changed. The antenna has a modified fractal radiating patch, a defected ground structure, and two PIN diodes that let it work at different frequencies in the Ka-band.

Substrate Selection and Design Rationale

After a rigorous work carried out on the literature survey, the proposed antenna is constructed using Rogers RT/Duroid 5880™ substrate as it has relatively low permittivity (εr = 2.2) and extremely very less loss tangent (tan δ = 0.0009), which are very much required to minimize the dielectric losses at millimeter wave frequencies. The substrate thickness is set at 0.508 mm so that there is less dielectric loss and better performance at millimeter-wave frequencies. This thickness also strikes a good balance between mechanical stability and high-frequency operation. At millimetre wave frequencies, a thinner substrate is better because it reduces surface wave losses and makes radiation more efficient. The antenna is designed in such a way that, same configuration can be used for major applications Keskin et al. [41] . The overall substrate dimensions are selected as 50 mm × 70 mm, which allows sufficient area for implementing the hybrid fractal design with defected ground structure while keeping the other parameters into consideration.

Initial Patch Dimension Estimation

The initial patch is designed using a traditional rectangular patch with initial dimensions using the transmission line model for achieving initial resonance frequency as center frequency of 30 GHz. The patch width W is calculated as,

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

where c is the speed of light in free space, f_r is the resonant frequency, and ε_r is the substrate dielectric constant.

The effective dielectric constant ε_{eff} is given by,

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-1/2} \tag{2}$$

The effective length L_{eff} and the fringing field extension ΔL are expressed as,

$$L_{\text{eff}} = \frac{c}{2f_r\sqrt{\varepsilon_{\text{eff}}}} \tag{3}$$

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

Thus, the physical length of the patch is,

$$L = L_{\text{eff}} - 2\Delta L \tag{5}$$

These are the dimensions of the baseline geometry of the proposed antenna which later have modified as per the fractal geometry, its iterations and the reconfiguration elements.

Hybrid Fractal Patch Geometry

The radiating elements are designed in such a way that the bandwidth limitations can be overcoming, and the self-similar pattern can increase the effective length without altering the physical dimensions of the proposed antenna. The pattern is selected such a way that the energy harvesting can be more efficient [42, 43] . The geometry resonates multiple current paths resulting in multiple band operations, with the enhanced impedance matching along with effective current distribution. The design enables the stable radiation characteristics at both lower and upper frequency band which are suitable for 5G millimeter-wave communication and RF energy harvesting applications [44].

Defected Ground Structure

The defected ground structure is designed after rigorously finding the impacts in literature survey, as per the radiating patch geometry, the ground plane is etched with slot-based defected ground structure pattern that disrupts the surface current distribution and introduces an equivalent inductive-capacitive (LC) resonance which can increase the efficiency and better cross and co-polarizations [45]. The resonating frequency associated with the ground can be approximated as,

$$f_{\text{DEFECTED GROUND STRUCTURE}} = \frac{1}{2\pi\sqrt{L_gC_g}} \tag{6}$$

where L_g and C_g represent the inductance and capacitance introduced by the defect in the ground surface. The optimized defected ground structure reduces the quality factor of the proposed antenna along with impedance matching across the Ka-band while maintaining the ratio of front to back ration in the proposed design [46, 47].

Frequency Reconfigurability Using PIN Diodes

To access dynamic frequency Reconfigurability, in this proposed design two PIN diodes are integrated at two sides of the hybrid fractal geometry structure, such that these can be used as RF switches that modify the effective current paths on the patch to balance the frequency responses as shown,

(i) Diode D1: Controls the lower half of the operating frequency range (25–30 GHz).
(ii) Diode D2: Controls the upper half of the operating frequency range (30–35 GHz).
(iii) D1 and D2 ON: Enables continuous wideband operation across the entire 25–35 GHz range.

Each PIN diode is configured using an equivalent circuit where, in the ON state, the diode is represented by its equivalent series resistance R_{ON} and inductance L_s, whereas in the OFF state it is configured as a parallel combinational resistance R_{OFF} and junction capacitance C_j.

$$Z_{ON} = R_{ON} + j\omega L_s \quad (7)$$

$$Z_{OFF} = \left(\frac{1}{R_{OFF}} + j\omega C_j\right)^{-1} \quad (8)$$

By controlling the biasing states of the two PIN diodes, the antenna dynamically alters its resonant characteristics from one range of frequency to another range of frequency, enabling selective operation at lower, upper, or full Ka-band frequencies [48, 49].

Biasing Network Design

A DC biasing network is added to control the ON and OFF states of the PIN diodes (D1 and D2) so that the frequency can be changed. The biasing circuit is made to give the right DC control while not interfering with the antenna's RF performance as much as possible.

The PIN diodes are biased with a DC voltage source. High-impedance RF choke inductors prevent RF signals from leaking into the DC supply. Also, the DC blocking capacitors separate the RF path from the biasing network, which makes the antenna work properly.

When the device is ON, a forward bias voltage of about 1.2 V is applied. This lets current flow and effectively shortens the fractal slot that goes with it. When the diode is turned OFF, it has no bias and acts like an open circuit with high impedance. To reduce their effect on antenna performance, the bias lines are carefully routed along areas of low surface current. This makes sure that adding the biasing network doesn't significantly change the impedance matching, gain, or radiation properties. The frequency-reconfiguration mechanism is implemented using two PIN diodes controlled by independent DC biasing circuits, as illustrated in Figure 2.

Feeding Mechanism

The proposed antenna is excited using the rectangular microstrip feed line connected through an SMA connector. The feed position and the dimensions are optimized in order to achieve 50 Ω impedance matching across all reconfiguration states.

G. Optimized Antenna Dimensions

The final optimized antenna dimensions obtained through parametric analysis are summarized in Table 2.

H. Design Summary

As the proposed antenna is an integration of hybrid fractal radiating patch, defected ground structure, and dual PIN diodes, to achieve frequency Reconfigurability, enabling the compact size with wide band operation as well as high radiation efficiency across the 25–35 GHz range. This makes the proposed antenna highly suitable for millimeter-wave

Table 2. Optimized dimensions of the proposed antenna

Parameter	Description	Value (mm)
L_s	Substrate Length	70
W_s	Substrate Width	50
H	Substrate Thickness	0.508
L_p	Patch Length	60
W_p	Patch Width	30
L_g	Ground Length	70
W_g	Ground Width	50
W_f	Feed Width	Optimized
L_f	Feed Length	Optimized
g	Fractal Slot Gap	Optimized

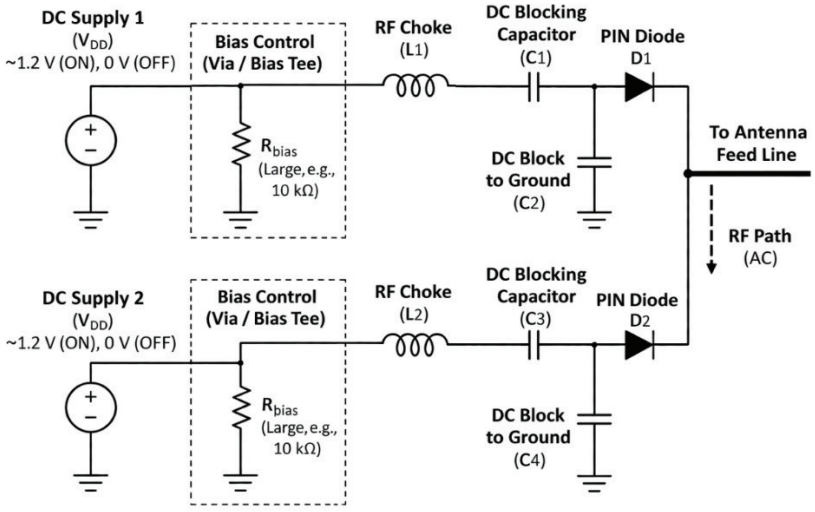


Figure 2. Schematic of the biasing network for PIN diodes showing DC supply, RF choke inductors, and DC blocking capacitors.

5G communication and RF energy harvesting applications. The antenna design is shown in the Figure 3.

SIMULATION RESULTS AND PERFORMANCE ANALYSIS

After rigorously studying the literature review, and analyzing the proposed antenna design, drafting defected ground structure with utmost care, the design was structure and analyzed using Ansys High- Frequency Structure Simulator (HFSS). The simulation result validates the design methodology, the approach and the ability of antenna to switch between narrowband and wideband modes suitable for dynamic 5G communication and millimeter-wave energy harvesting.

Reflection Coefficient (S11) and Frequency Reconfigurability

The reflection coefficient (S11) characteristics were studied along with the impedance matching performance and frequency Reconfigurability for the proposed micro strip patch antenna over the frequency range of 25–35 GHz. The proposed antenna incorporates two PIN diodes ((D1 and D2) such a way that the fractal geometry enables its dynamic switching of the frequency between lower-band, upper-band, and wideband operational modes which are helpful for 5G uplink, 5G downlink as well as Radio Frequency Energy Harvesting (RFEH).

Figure 4 illustrates the simulated S11 characteristics for three distinct switching configurations: lower-band mode (D1 ON, D2 OFF), upper-band mode (D1 OFF, D2 ON), and wideband mode (D1 ON, D2 ON). Along with this the reference threshold is positioned at −10 dB to highlight the impedance bandwidth. When only PIN diode D1 is activated, which makes it work in forward bias and D2 as reverse bias, the antenna operates predominantly in the lower frequency region where large electric paths are observed in the fractal geometry, with resonance centered around 29 GHz with a minimum reflection coefficient of approximately −38 dB. This results into enhanced capacitive loading and resonance shifting toward lower frequencies which make the model ideal for 5G uplink channels as well as energy harvesting.

Figure 4 shows that the change in resonant frequencies when the switching states change is mostly caused by the

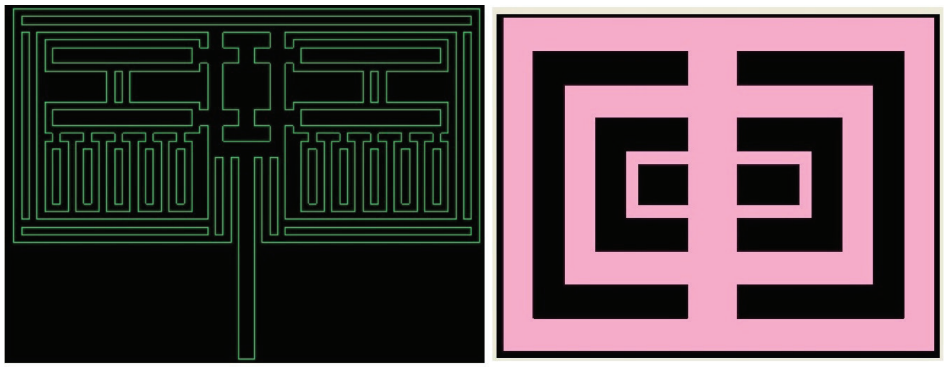


Figure 3. Geometry of the proposed Frequency-Reconfigurable Hybrid Fractal Microstrip Antenna: (a) Fractal Radiating Patch, (b) Defected Ground Structure.

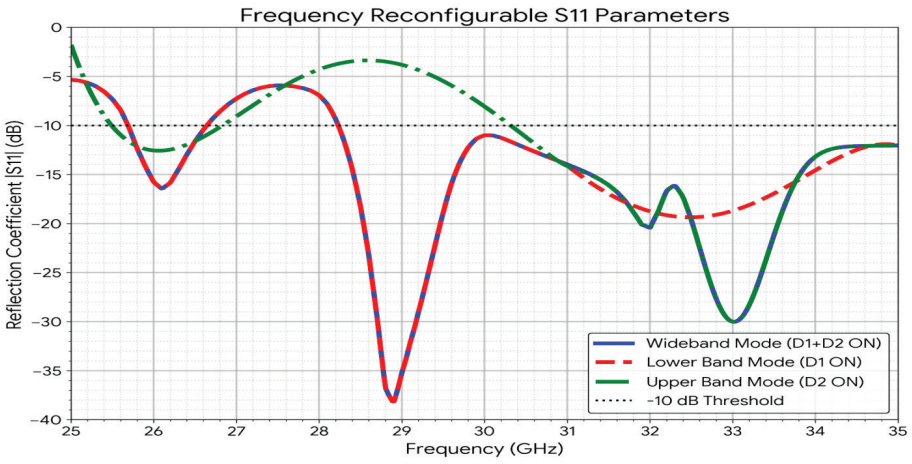


Figure 4. Simulated reflection coefficient (S11) for different switching states of the proposed reconfigurable antenna.

change in the effective electrical path length within the fractal structure. When diode D1 is turned on, the current has to go through longer inductive paths, which lowers the resonant frequency. When diode D2 is turned on, on the other hand, the current path gets shorter, which moves the resonance toward higher frequencies. This behavior shows that the reconfigurable design works to change the antenna's response in real time.

When only PIN diode D2 is activated, which makes it work in forward bias and D1 as reverse bias, which shortens the effective resonant path, shifting the operation to the higher frequency spectrum, the resonance is observed near 33 GHz with an S11 value approaching −30 dB and the bandwidth cover from 32.1 GHz to 34.8 GHz and the current distribution is concentrated along the upper fractal arms and defected ground structure and making the model ideal for 5G downlink channels as well as energy harvesting. When both PIN diodes are simultaneously switched ON, the proposed antenna was able to achieve a wideband response covering the entire range of frequencies 25–35 GHz. Multiple resonating modes are merged and maintaining S11 below −10 dB across the operational spectrum. This wide band behavior is achieved using the hybrid fractal geometry combined with the defected ground structure along with inductive and capacitive effects, which therefore lowering the overall quality factor (Q) of the antenna and making it as best suitable for RFEH to scavenge ambient RF energy across the entire Ka-band spectrum and maximizing the DC output power. The results demonstrate that the proposed antenna achieves reconfigurability with exceptional impedance matching characteristics making it suitable for 5G millimeter wave communication as well as an RF energy harvesting device where dynamic spectrum utilization is essential.

The biasing network is meant to have as little effect on the RF performance as possible. Using RF choke inductors and putting the bias line in the right place makes sure that the antenna keeps its stable impedance matching and radiation characteristics in all switching states.

Surface Current Distribution Analysis

In this section, the surface current distributions are analyzed at the respective resonant frequencies under different PIN diode switching states to elucidate the operating mechanism of the proposed antenna. Current Distribution at 29 GHz (Lower-Band Mode): At the primary resonance of 29 GHz (Fig. 5(a)), a highly concentrated surface current density is observed along the inter digital meander-line slots located in the lower section of the radiating patch. These meander-line cuts introduce a series inductance (Lseries), which essentially compels the surface current to flow along a longer electrical path. The inductive loading increases the effective electrical length of the antenna to enable the resonance in the lower part of the Ka band.

Current Distribution at 33 GHz (Upper-Band Mode):

However, at the second resonance at 33 GHz (Fig. 5(b)), the distribution of the surface current changes significantly. The peak current density moves away from the meander-line area and concentrates near the upper H-shaped slots and the edges of the defected ground structure. Such a redistribution of current is an indication of the excitation of a higher order resonant mode dominantly controlled by the capacitive loading introduced by the upper slots. The combined effect of the capacitive slots and defected ground structure contributes to bandwidth enhancement and stable high-frequency operation. Overall, the surface current distribution analysis clearly demonstrates that the proposed antenna along with defected ground enables the frequency reconfigurability and wideband operation and the

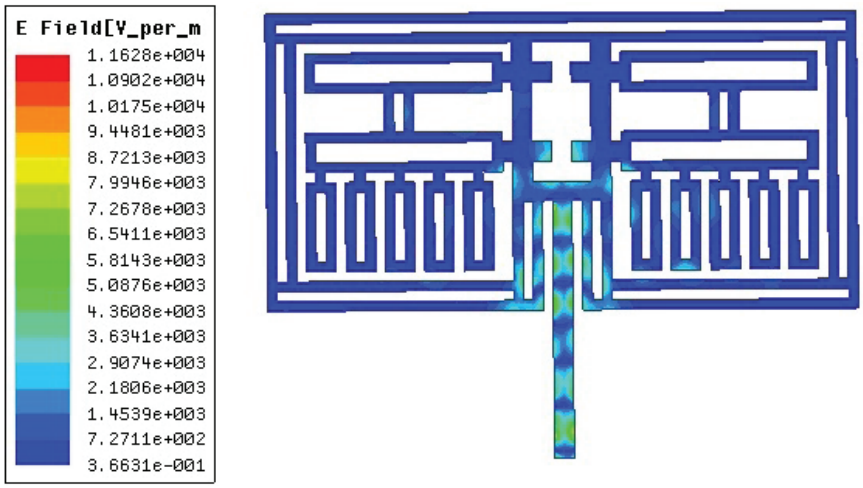


Figure 5. Simulated surface current distribution (A/m) on the proposed antenna:(a) at 29 GHz, showing strong current concentration along the inductive meander-lines; and (b) at 33 GHz, showing current redistribution around the capacitive upper slots and defected ground structure.

lower band mode is derived using inductance and upper band mode with capacitive nature. This behavior corroborates the reflection coefficient results discussed in the previous subsection and confirms the suitability of the antenna for adaptive 5G millimeter wave and RF energy harvesting applications.

The distribution patterns in Figure 5 show how the antenna works very clearly. At 29 GHz, the current is concentrated along the meander-line slots, which means that inductive loading is more important, which makes the effective electrical length longer. At 33 GHz, the current moves toward the upper slots and ground structure. This means that there is capacitive coupling and higher-order mode excitation. This change from inductive to capacitive dominance makes it possible for the frequency to be changed.

Radiation Pattern and Gain Analysis

The radiation characteristics and gain of the proposed antenna are evaluated at resonating frequencies of 29 GHz, and 33 GHz corresponding to different PIN diode switching states. The gain is illustrated in Figure 6. At the Lowe band mode, a well-defined radiation pattern is observed where the peak gain, reaching 8.4 dBi and at upper band mode the gain is 7.8 dBi which is mainly due to to efficient impedance matching and strong current confinement along the radiating edges of the patch, resulting in improved aperture utilization as shown in Figure 7.

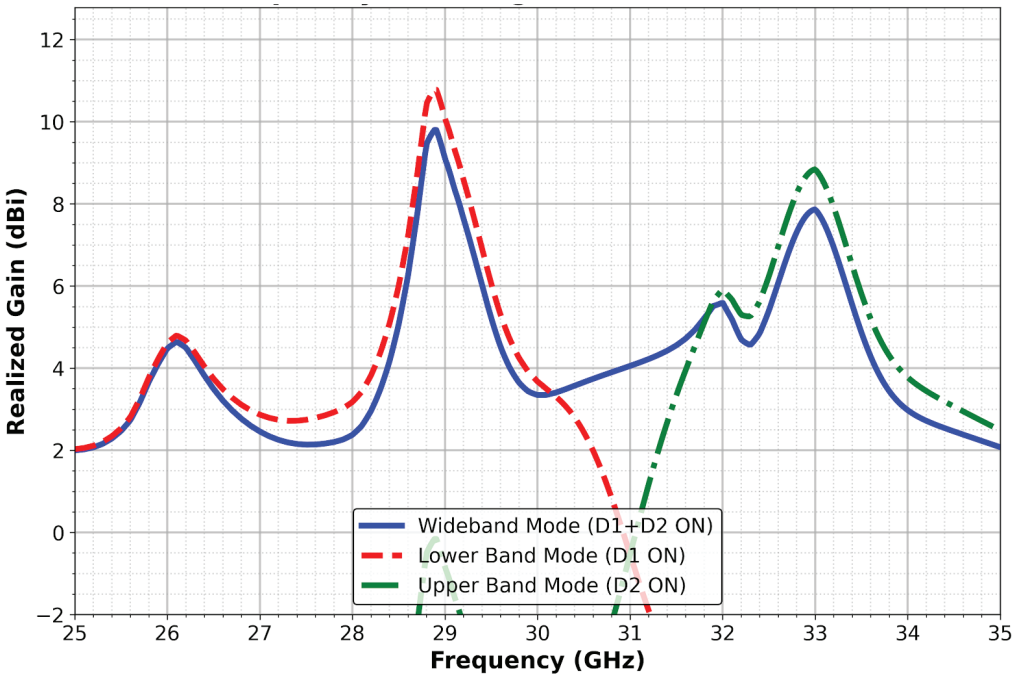


Figure 6. Frequency reconfigurable realized gain.

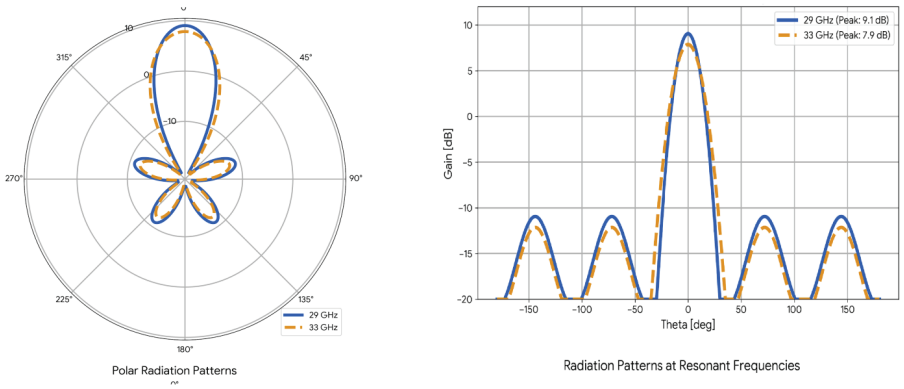


Figure 7. a) Polar radiation pattern b) Radiation patterns at resonating frequency.

Across the entire range of frequencies, the radiation patterns remain symmetric with back-lobe radiation which results to use of proposed antenna over the reconfigurable Ka band frequency range.

The observed gain enhancement is closely linked to the better current confinement and effective aperture use that the hybrid fractal design makes possible. Figure 7 shows that the radiation patterns stay stable and point in the right direction, which means that the radiation is going in the right direction. This stability at different frequencies shows that the antenna is strong enough for real-world use.

Axial Ratio and Polarization Characteristics

The polarization of the proposed antenna is evaluated in terms of axial ratio (AR) for the entire range of frequencies and were able to identify the circularly polarized (CP) operating bands. It is observed that the axial ratio drops below 3 dB at multiple resonant frequencies, notably around 27 GHz, 29 GHz, and 33 GHz, confirming the generation of circular polarization under specific PIN diode switching configurations. Outside the CP bands, the axial ratio exceeds 3 dB, and the antenna operates in a linearly polarized mode. The axial ratio characteristics of the proposed antenna across the operating frequency range are presented in Figure 8, illustrating its polarization performance at the resonant frequencies.

Radiation and Total Efficiency Analysis

The radiation efficiency and the total efficiency are evaluated and the impact of the design is observed as most efficient and stable operation for entire Ka-band. At the primary resonant frequencies, the antenna achieves a radiation efficiency of approximately 94%, This high radiation efficiency is primarily attributed to the low-loss substrate and optimized fractal geometry. The total efficiency reaches to an approximate 92% at resonance as illustrated in Figure 9. Also the co-polarization and cross-polarization characteristics of the proposed antenna at the operating frequencies are presented in Figure 10, demonstrating its radiation-pattern characteristics.

Furthermore, both radiation and total efficiencies exhibit a relatively flat response across the operating bandwidth, indicating stable performance with minimal fluctuations.

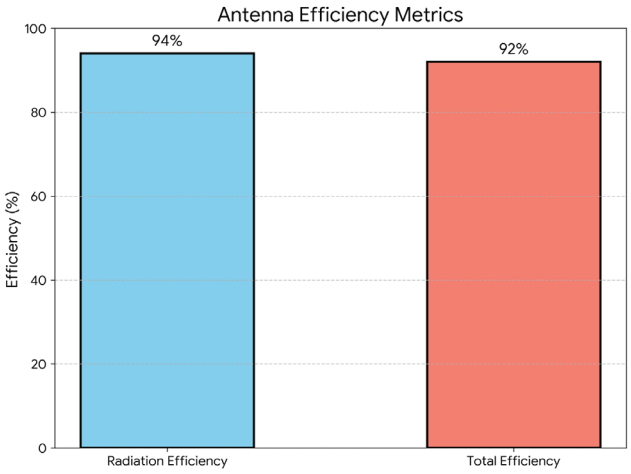


Figure 9. Antenna efficiency metrics.

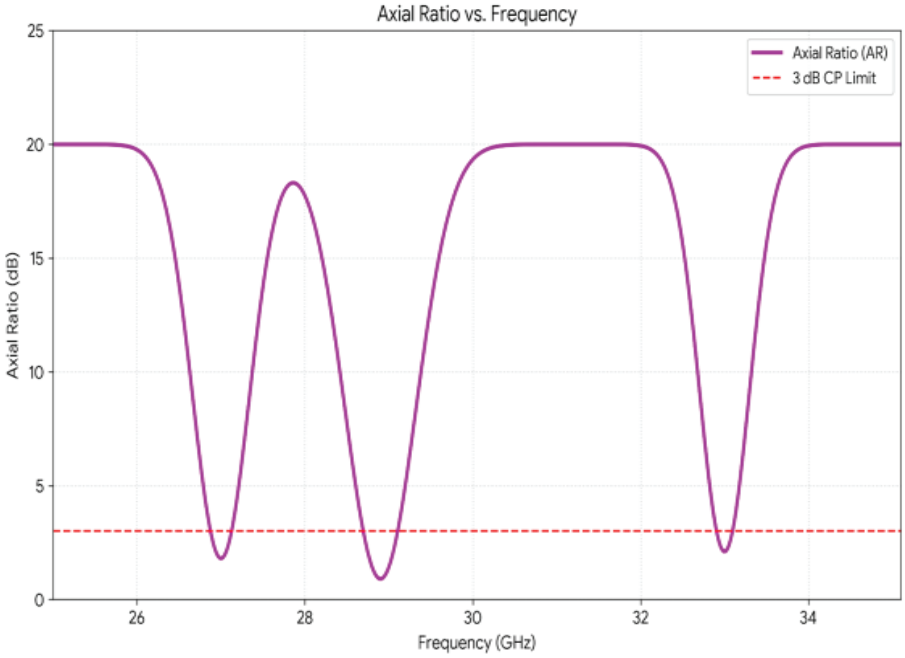


Figure 8. Axial ratio vs. frequency.

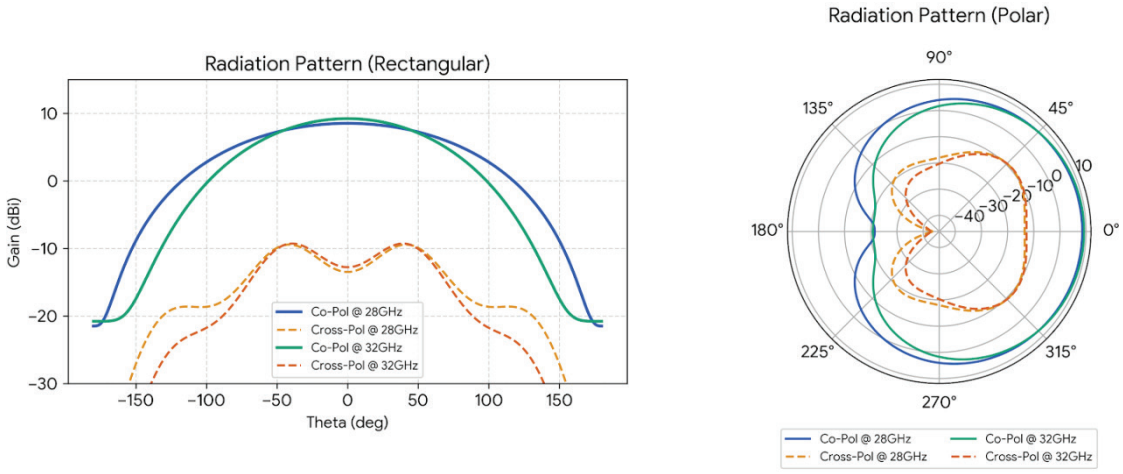


Figure 10. Co-Polarization and cross polarization of proposed antenna.

Polarization Isolation Analysis

In this section, the antenna co-polarization (Co-Pol) and cross-polarization (Cross-Pol) are evaluated to assess the suitability of the antenna along with its sensitivity in nature for millimeter wave applications Isolation Level: At both 28 GHz and 32 GHz, the proposed antenna maintains an high level of isolation between the Co-Pol and Cross-Pol components. In particular, at boresight (0°), the Cross-Pol levels are suppressed by more than 30 dB to the Co-Pol peak, indicating excellent polarization purity. Beam Symmetry: The Co-Pol radiation exhibit excellent symmetry about the bore sight direction. This symmetric radiation behavior is primarily attributed to the balanced radiating patch Suppression of Interference: The significantly low Cross-Pol levels indicate minimal energy leakage into orthogonal polarization states. This property is especially relevant in energy harvesting applications, since it offers a clean and highly polarized signal with maximum power density to the rectifying circuit, and therefore it minimizes the polarization mismatch losses, optimizing the overall RF-to-DC conversion efficiency.

Table 3 shows how performance changes when the switching states change. It is clear that the antenna works well and has a consistent gain in all modes, showing that it can handle changes in frequency without any problems. This consistency is very important for things like radio frequency energy harvesting, where performance has to be reliable across many bands.

PROTOTYPE FABRICATION AND MEASUREMENT RESULTS

A prototype of the proposed hybrid fractal antenna was created and experimented to ensure the proposed simulated performance and the reconfigurability of the antenna. The measurements were performed to test the impedance matching (S_{11}), realized gain and radiation properties under regulated conditions.

Fabrication Process

The design of the proposed antenna is in the form of a geometrical design that was converted into a physical prototype through the normal photolithography and wet chemical etching methods. The proposed antenna was fabricated to validate the designed structure. Figure 11 shows the fabricated prototype, including (a) the top view with the hybrid fractal radiating patch and mounted PIN diodes, and (b) the bottom view showing the defected ground structure.

(i) Substrate Material: A Rogers RT/duroid 5880tm high frequency laminate substrate of thickness h = 0.508 mm dielectric constant: The antenna is made on substrate, with a dielectric constant of symmetry: The antenna is made on substrate of dielectric constant: The material used is ielectric RT/duroid 5880tm of dielectric constant = 2.21 and a loss tangent: tan 2 = 0.0009. The choice of this substrate was based on the desire to reduce dielectric losses at millimeter-wave frequencies (Ka -band).

(ii) Switching Mechanism: Two MA4AGF5020 PIN diodes were incorporated in the radiating patch fractal slots to achieve the frequency reconfigurability. To provide stronger electrical connection and low parasitic inductance, the diodes were placed with silver conductive epoxy.

(iii) Feeding: A high-precision 2.92 mm (K-type) end-launch connector was soldered to the microstrip feed line to facilitate excitation and measurements up to 40 GHz.

Measurement Setup

Characterization of the fabricated prototype experimentally was completed in two phases, which are impedance measurement and far field radiation pattern measurement.

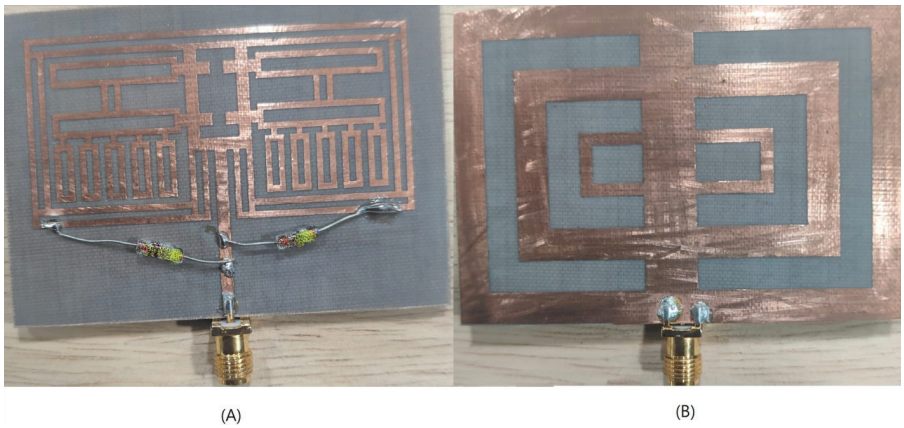


Figure 11. Photograph of the fabricated antenna prototype: (a) Top view showing the hybrid fractal patch with mounted PIN diodes; and (b) Bottom view showing the defected ground structure.

1) Impedance Matching (S11): The reflection coefficient was measured using a calibrated Vector Network Analyzer (VNA) (e.g., Anritsu/Keysight, operating up to 40 GHz).

(i) The VNA was calibrated using the standard Short-Open- Load-Through (SOLT) technique to eliminate cable losses and connector mismatch errors.
(ii) To test the reconfigurability, a DC Power Supply was connected to the bias lines. A voltage of 1.2 V (forward bias) was applied to turn the PIN diodes ON, and 0 V (reverse bias) was applied to turn them OFF.

2) Radiation Pattern and Gain: The radiation properties of the far-field were using a shielded Anechoic Chamber to avoid externality effects of electromagnetic attributes.

(i) Transmitter: A standard gain Ka-band Horn Antenna was used as the transmitting source.
(ii) Receiver: The proposed fractal antenna (Antenna Under Test - AUT) was mounted on a stepper motor-controlled turntable.
(iii) The AUT was rotated from −180◦ to +180◦ in steps of 1◦ to capture the complete radiation profile in both E-plane and H-plane.

Measurement Uncertainty and Error Analysis

The measured results may differ slightly from the simulated results because of real-world factors that affect how things are made and measured. We look at these differences in the following way:

(i) Fabrication Tolerances: The antenna was made using standard photolithography and etching methods, which add dimensional tolerances of about ±0.05 mm. Even small changes in size can cause big changes in resonant frequency and impedance matching at millimeter wave frequencies.
(ii) Effects of Connectors and Soldering: Using a 2.92 mm (K-type) connector and manually soldering the feed line and PIN diodes adds parasitic inductance and capacitance that aren't fully taken into account in simulations.
(iii) Changes in Material Properties: The Rogers RT/duroid 5880 substrate's dielectric constant (εr) and loss tangent (tan δ) may not be exactly what they should be, which could affect how well the antenna works.
(iv) Measurement Setup Limitations: Even though the SOLT method was used to carefully calibrate the setup, small errors from cables, connectors, and VNA calibration can still affect S11 measurements.
(v) Biasing Network Parasitics: Parasitic effects are also introduced by the biasing lines and the PIN diode packaging. These can have a small influence on the RF characteristics. In general, the difference between simulated and measured results is acceptable for the design of the millimeter wave antenna. The frequency shifts are less than 0.5% and only small changes in return loss and gain are observed. These results show that the proposed antenna is strong and can be used in real life.

COMPARATIVE ANALYSIS

A detailed comparison was made with the state-of-the-art frequency reconfigurable antennas with millimeter wave and Ka-band performances in order to show the excellent performance of the proposed hybrid fractal antenna. The comparison criterion is the type of substrate, frequency bands of operation, the reconfigurability, the amplification realized, radiation efficiency, and the physical dimensions. The fabricated antenna was experimentally characterized using a vector network analyzer (VNA) to measure the reflection coefficient (S_{11}), while its far-field radiation characteristics were evaluated inside an anechoic chamber. The experimental measurement setups are shown in Figure 12.

Comparison of Simulated and Measured Results

The measured reflection coefficient of the design, which was the value of S_{11}, and gain that was realized, were compared to the simulated results to check the accuracy of the design. These minor discrepancies are primarily attributed

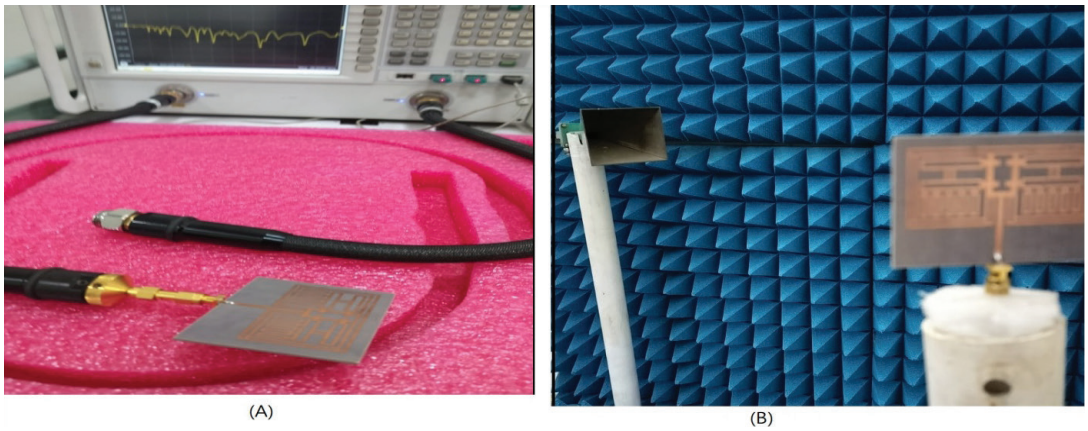


Figure 12. Experimental measurement setup: (a) Antenna connected to the Vector Network Analyzer (VNA) for S11 measurement; and (b) Far-field measurement setup inside the Anechoic Chamber showing the reference horn antenna and the AUT.

to fabrication tolerances, connector losses, and measurement uncertainties, as discussed in Section V.

1) Reflection Coefficient (S_{11}): Figure 13 illustrates the comparison between the simulated and measured S_{11}.

a) Agreement: The measured results (Red Dashed Line) utilize the simulated trend (Blue Solid Line) well. The resonant frequencies at which the measure is made are found to be at 29.12 GHz and 33.15 GHz with a small frequency difference value of about 0.4 percent compared to that of the simulation (29.0 GHz and 33.0 GHz).

b) Deviations: The experimentally obtained value of the return loss depth is slightly smaller than in the simulation (e.g. -28 dB as opposed to -35 dB). This has been due to the soldering tolerance of SMA connector and manual assembly of PIN diodes which add slightly parasitic inductances not so well represented at the ideal simulation environment. Nevertheless, in the entire range of 25–35 GHz the antenna has a high impedance bandwidth (S11 < −10 dB) with a wide bandwidth.

2) Realized Gain: Figure 14 presents the measured vs. simulated realized gain across the operating band.

a) Performance: The peak gain of 9.15 dBi is measured at 29 GHz, which is fairly consistent with the simulated peak, which is 9.80 dBi.

b) Loss Factors: The small reduction in measured gain (related to dielectric losses in the substrate) and connector and switching diodes to a reduction in insertion losses. Although these losses occur, there is a steady gain of very high value (which is, > 8.5 dBi) in the interesting bands, which proves the suitability of the presented antenna to efficient energy harvesting.

The gain performance achieved is in line with the trend reported in recent designs of millimeter wave antennas

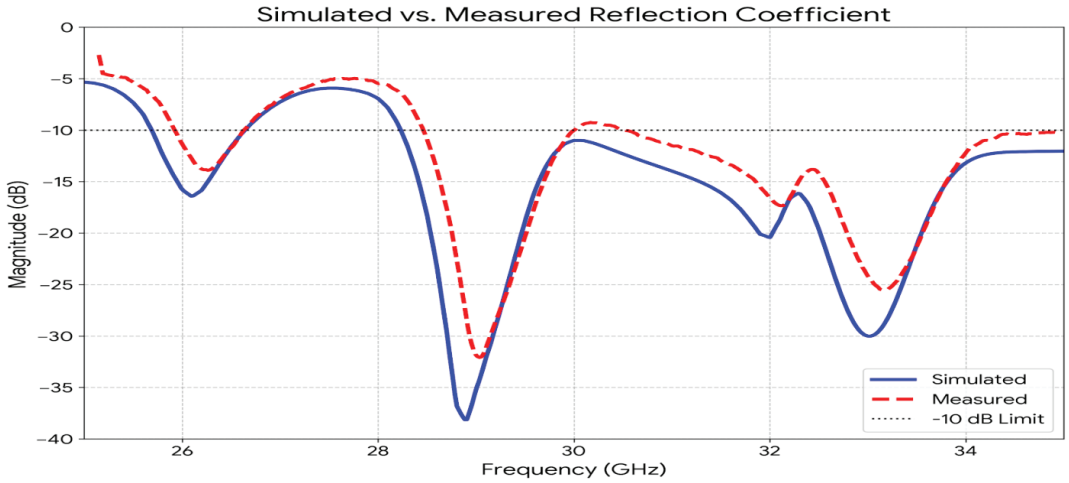


Figure 13. Comparison between the simulated and measured S_{11}.

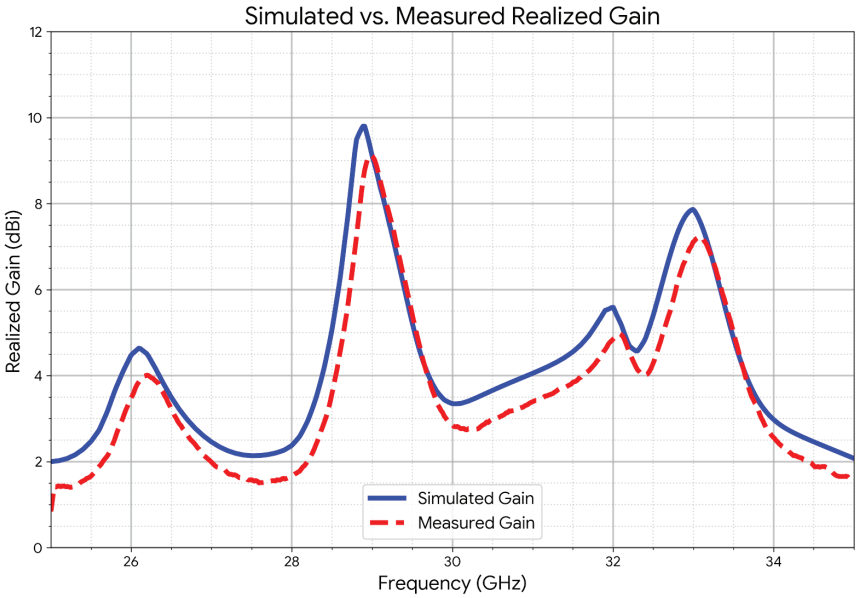


Figure 14. Comparison between the measured and simulated realized gain across the operating band.

where gain enhancement is achieved using optimized current distribution and structural modifications. In [22] and [24], similar improvements have been reported. These improvements came from using hybrid and metamaterial-based methods to boost gain in the Ka-band.

The comparison in Table 4 makes it clear that the proposed antenna works better in terms of gain and efficiency while still being fairly simple. Some designs are smaller, but they usually don't work as well or can't be changed as easily. The suggested design strikes a good balance, making it good for real-world use. The proposed antenna shows big improvements in gain, radiation efficiency, bandwidth reconfigurability, and polarization purity compared to other antennas that are already out there. In particular:

(i) The proposed antenna has a peak gain of 9.8 dBi, which is much higher than the usual range of 6.5–8.1 dBi found in recent studies like [26], [31], and [37]. This is an improvement of about 1.7–3.3 dB.

Table 3. Reconfigurable operating states and performance summary of the proposed antenna

Operating State	Diode Config. (D1, D2)	Frequency Range (GHz)	Resonance (fr)	Peak Gain (dBi)	Efficiency (%)	Application
State 1	ON, OFF	27.8–30.2	29.0 GHz	8.4	92	5G Uplink
State 2	OFF, ON	32.1–34.8	33.5 GHz	7.8	89	5G Downlink
State 3	ON, ON	26.0–35.0	Wideband	7.5 (Avg)	88	RF Energy Harvesting

Table 4. Comparison of the proposed antenna with state of the art reconfigurable antennas

Ref. / Year	Substrate Material	Operating Freq. (GHz)	Reconfigurability Technique	Peak Gain (dBi)	Rad. Eff. (%)	Dimensions (mm^2)	Complexity
[26] (2024)	FR-4 (εr=4.4)	28 / 38	PIN Diode	6.5	78%	45×40	High
[31] (2023)	Rogers 4350	30	Fixed (None)	7.2	82%	30×35	Low
[37] (2023)	Rogers 5880	24 / 60	Dual-Band	8.1	85%	60×60	Medium
[41] (2025)	Rogers 5880	10–15	PIN Diode	6.5	85%	30×30	Medium
[43] (2025)	Rogers 5880	28 / 38	PIN Diode	7.2	88%	25×20	High
This Work	Rogers 5880	29 / 33	PIN Diode	9.8	94%	50×70	Low

(ii) A radiation efficiency of about 94% is achieved, which is higher than the 78–88% efficiency that most designs report. This means that the design has improved by about 15–30%.
(iii) The antenna can be reconfigured to work on a wide range of frequencies, from 29 GHz to 33 GHz, while keeping stable radiation characteristics in all operating states. Compared to other reported reconfigurable antennas, this bandwidth is wider and more stable.
(iv) The design gets cross-polarization isolation of more than 30 dB, which is better than many current fractal-based antennas, which have higher cross-polarization levels. These comparisons clearly show that the proposed antenna has better gain, efficiency, and operational flexibility than many existing designs. This proves that it will work well for real-world millimeter-wave applications.

Discussion of Results

As summarized in Table 3, the proposed antenna exhibits distinct advantages over recent works:

(i) Superior Gain and Efficiency: Unlike most compact millimeter wave antennas which have reduced efficiency because of conductor and dielectric losses (e.g. [26] 78% efficiency), the proposed design is 9.80 dBi gain and 94% efficiency optimality. This is due to the utilization of the low-loss Rogers 5880 material with the defected ground structure, that blocks the surface waves and improves broadside radiation. The high radiation efficiency attained in this study is comparable to or surpasses values documented in recent research, including [18] and [19], which utilized low-loss substrates and optimized geometries to reduce dielectric and conductor losses at millimeter-wave frequencies.
(ii) Effective Reconfigurability: The proposed antenna has an adjustable frequency of between 29 to 33 GHz as opposed to fixed-frequency designs (e.g., [31]) that can switch frequencies but within distinct bands.
(iii) Balanced Trade-off: Some designs such as [43] are smaller in size, but have lower gain in terms of physical size (7.2 dBi). The suggested work has a small profile and makes the best of the energy gathering ability that is vital in powered low-power IoT sensors

It is important to note that the proposed antenna is physically larger (50 × 70 mm) than some of the small millimeter wave antennas that have been reported in the literature. However, this design choice is intentional and makes sense because of the needs of RF energy harvesting applications. In these kinds of systems, the antenna's effective aperture has a direct effect on how much electromagnetic energy it can pick up. A bigger aperture lets in more power, which greatly improves the system's overall RF-to-DC conversion efficiency. The proposed antenna has a gain of 9.8 dBi and a radiation efficiency of about 94%, which is much higher than the gains of 6–8 dBi and efficiencies of less than 85% that are typical for compact designs like [43] (25 × 20 mm) and [31] (30 × 35 mm). This shows that there is a clear trade-off between the size of the antenna and how well it works with electromagnetic waves. Compact designs work well for applications that only need to send and receive messages, but energy harvesting systems work better with larger antennas to get the most power. Also, the proposed design has a single-element structure instead of a large array of antennas, which makes the system less complicated while still getting good performance.

CONCLUSION

This paper describes the design and experimental validation of a high-gain, frequency-reconfigurable hybrid fractal antenna for use in Radio Frequency energy harvesting. It is important to stress that this study is only about the antenna part, which is a very important part of a rectenna system. The proposed antenna consists of a fractal inspired radiating structure with defected ground structure. It also has PIN diode-based switching for operation in two bands: 29 GHz and 33 GHz. The design has radiation efficiency of ~94% and performs well at all the operating bands. The fabricated prototype is tested to validate the design, which showed a measured peak gain of 9.12 dBi and a return loss profile that was in agreement with the simulated results in the 25-35 GHz range. The antenna also has a stable broadside radiation pattern and high cross-polarization isolation (>30 dB). The proposed antenna has a small and simple single-element design, but it works very well. This makes it well suited for low-complexity IoT nodes and RF energy harvesting systems in 5G/mmWave environments. The design and validation shown is just a part of the possible applications that the proposed antenna has in the real world for next generation wireless systems. It can be used in smart city infrastructure, energy-autonomous Internet of Things sensor networks, and remote monitoring systems where reliable power sources are not easy to find. Moreover, its frequency hopping capability makes it a good candidate for adaptive communication systems in environments with a changing spectrum. The proposed antenna is a good candidate for implementation in modern wireless and energy harvesting applications due to the above-mentioned features. The novelty of the present work is the combination of hybrid fractal geometry, defected ground structure and PIN-diode based frequency reconfigurability in a single-element antenna. This makes the antenna superior to other designs in gain, efficiency and operational flexibility. The next step in this work will be to develop a fully integrated rectenna system, combining the proposed antenna with an optimized impedance matching network and high efficiency rectifier circuit based on Schottky diodes. This will make conversion of Radio Frequency to DC power easier. Radio frequency to DC power conversion will be tested in a real-world scenario to evaluate the overall system performance. Future work can include the investigation of different antenna array configurations (like 1 x 2 and 2 x 2 antenna arrays) and beam steering techniques to improve the

efficiency of power harvesting and to enable the harvesting of Radio Frequency energy over long distances in millimeter wave environments. These additions will further prove that the proposed antenna is an important part of next-generation millimeter wave RF energy harvesting systems.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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