An Anti-Symmetric Half Koch-Minkowski Offset Fed Hybrid Fractal Antenna for Sub-6GHz and S-band

Atul Varshney[1], Sanjay Singh[1], Issa Elfergani [2,3] , Chemseddine Zebiri[4], Jonathan Rodriguez[2,5]
atulgkvright@gmail.com[1], sanjaysingh89ind@gmail.com[1]
i.t.e.elfergani@av.it.pt[2.3], Jonathan@av.it.pt[2], czebiri@univ-setif.dz [4], ash.hussaini@aun.edu.ng[5]
[1] ECE Department, FET,Gurukula Kangri (Deemed to be) University, Haridwar249404, Uttarakhand, India[1]
[2] The Instituto de Telecomunicações, Campus Universitário de Santiago, Aveiro 3810-193, Portugal.
[3] School of Engineering and Informatics, University of Bradford, Bradford BD7 1DP, UK.
[4] Laboratoire d'Electronique de puissance et commande industrielle (LEPCI), Department of Electronics, University of Ferhat Abbas, Setif -1- , Setif 19000, Algeria.
[5] School of Engineering, American University of Nigeria, Yola 640230, Nigeria

Abstract. This article presents the design, fabrication, and measurements of an offset edge-fed hybrid fractal antenna for sub-6GHz and S-band applications. The antenna comprises a compressed partial ground structure and the hybrid fractal patch of the antenna is developed from a rectangular patch by subtracting an anti-symmetric mirror combination of half Koch and Minikowski curves. The antenna is designed using an HFSS electromagnetic simulator at a frequency of 3.3GHz. The lowest reflection coefficients <-10dB fractional bandwidth at resonant frequencies are -27.87dB, and -20.60dB with a peak gain of 3.90 dBi and maximum radiation efficiency of 84.50% at 3.3GHz. The prototype model of the antenna fabricated on an FR-4 substrate exhibits dual bands (2.23GHz to 3.80GHz), and (4.11GHz to 4.35GHz). The antenna is resonating at frequencies of 3.3GHz, and 4.3GHz respectively. Therefore, the designed antenna is most suitable for Bluetooth, Wi-Fi, and ISM band (2.45GHz), WLAN(3.65–3.70 GHz) (802.11b/g) (2.4-2.483GHz), Wi-Max (2.3GHz, 3.4–3.6 GHz), LTE (3.2–3.3 GHz), n77(3.7GHz), n78(3.3–3.67 GHz), n40(2.3GHz), and S-band (2.25-3.85GHz) C-band(4.11-4.15GHz, 4.24-4.35GHz) applications.

Keywords: Half-Koch curve, Minkowski curve, Monopole Antenna, Offset feed, Sub-6GHz, Dual-band Antenna.

1 Introduction

Multiband technology in microwave communications is a way for people to communicate (mostly with a cell device) that accepts and transmits various radio frequencies. Possessing or deploying distinct bands, specifically frequency bands. All cellular devices and consoles are linked to Wi-Fi networks. Aside from these, Wi-Fi has a wide range of applications. Internet of Things (IoT) applications use integrated circuits and chipsets that are wirelessly linked to a cloud server. Because of the large variety of Wi-Fi applications, the antenna used to transmit and receive Wi-Fi signals must be compact so that it can be housed within the device and have wider bandwidth [1]. The size of the antenna must be decreased further to meet global demand for small wireless products. A great deal of research has been done on planar antennas. Most tiny devices employ a patch antenna that operates in the ISM band and has a resonance frequency of 2.4 GHz for short-distance communications [2, 3]. Palandöken. et al. proposed a

IMDC-IST 2023, October 25-27, Yola, Nigeria

DOI 10.4108/eai.25-10-2023.2348732

shaped antenna has the lowest gain and radiation efficiency at the lower frequency of 2.4GHz [4]. To achieve high gain the design has a complex structure with a four-element rectangular patch antenna array which can be utilized for amateur radio applications in the S-band only [5]. A curved monopole antenna is made which is having still a small gain at the resonant frequency of 2.4GHz [6]. It is noticed from the literature that different feeding techniques have been used to excite microstrip antennas. The most widely used feeding mechanisms involve coaxial feed, edge feed, inset feed, proximity feed, and quarter wave impedance transformer feed [1-11]. Sharma et al., have designed and fabricated a Koch Minkowski hybrid fractal dual narrow band antenna at a design frequency of 3.2GHz [12]. Balani, W., et al. have fabricated and demonstrated an ear-shaped circular wideband fractal multi-tuned antenna whose gain varies between 0.2 to 9.7dBi [13]. Abdelaziz, A., et al., have designed a compact high gain tri-band symmetrically spaced dual T-slotted rectangular patch antenna with a maximum gain of 11.72 dBi[14]. Liu, S. et al have explained and fabricated a double U-slotted dual band antenna that exhibits 8.6dBi maximum gain [15]. Kaur, N. and Sharma, N., have designed and presented a multi-narrow band of Koch-Minikowski slotted fractal patch inset feed antennas for S-band, C-band, and X-band applications [16]. Varshney, A., et al., have designed and optimized a fractal compact miniaturized spearhead antenna using a transformer feed line for 5G mobile and Sub-6GHz applications [17]. Bangi, I. S., and Sivia, J. S., have presented a hexa-tuned Minikowski-Koch hybrid fractal compact antenna that exhibits 6.09dBi gain for narrow band applications [18]. Fonseca, D., et al., have demonstrated a penta-tuned narrow band double Koch-slotted fractal antenna for wireless and microwave applications [19].

The main objective of this work is to design a monopole multiband antenna by the use of a hybrid offset feeding technique at a frequency of 3.30GHz. The hybrid feed is nothing but a combination of inset feeding and center-shifted edge feeding techniques. The advantage of this feeding technique is to get a tremendously reduced antenna size than existing literature antennas at the same frequency. Another aim of this article is to achieve fractal length controlled second resonant frequency for flexible applications.

This article describes the design, fabrication, and measurements of an economic, compact, easy-to-fabricate, anti-symmetrical half Koch-Minikowski hybrid curve offset-fed monopole antenna for Sub-6GHz applications. This article includes the antenna geometry with reflection coefficients, electric-field vector and current density distribution, radiation patterns, antenna axial ratio, and plots at the two resonant frequencies.

2 Methods and Materials

The proposed compact antenna (37.26mm × 38.49mm) is fabricated on a low profile 1.6mm thick FR4 substrate at a design frequency of 3.3GHz with permittivity 4.4.

2.1 Antenna Structure

The following design equations are used for general rectangular microstrip patch antenna (RPA) calculations [7, 8];

Step 1: The width of the radiating RPA is given by the equation:

$$W = \frac{c}{2f_0}\sqrt{\frac{2}{\mathscr{E}_r+1}} \qquad (1)$$

Where:

c: velocity of light is 3×10^8m/s,

$\mathscr{E}_r$: Dielectric constant of the substrate.

f_0: design frequency of the antenna

Step 2: Effective Dielectric constant of the PRA is determined as:

$$\mathcal{E}_{reff} = \frac{\mathcal{E}_r+1}{2} + \frac{\mathcal{E}_r-1}{2}\left[\frac{1}{\sqrt{1+\frac{2h}{w}}}\right] \quad (2)$$

Step 3: The effective length is at the design frequency

$$L_{eff} = \frac{C}{2f_0\sqrt{\mathcal{E}_{eff}}} \quad (3)$$

Step 4: Extension length of the PRA compute with this equation:

$$\Delta L = 0.412h\frac{(\mathcal{E}_{eff+0.3})\,(\frac{W}{h}+0.264)}{(\mathcal{E}_{eff-0.258})\,(\frac{W}{h}+0.8)} \quad (4)$$

The length " L" of the PRA is calculated as:

$$L = L_{eff} - 2\,\Delta L \quad (5)$$

Step5: Radiation box Calculation

$$\lambda = \frac{c}{f_0} \quad (6)$$

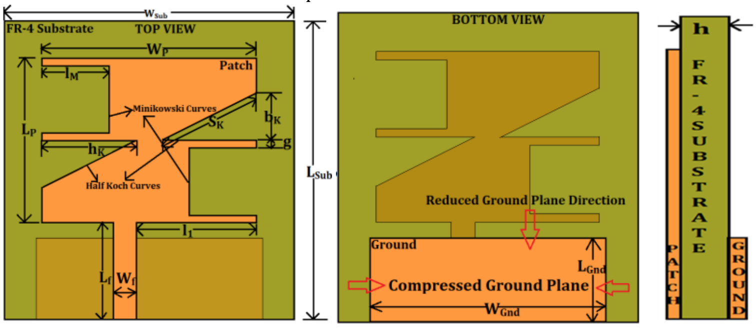
$$\lambda_g = \frac{\lambda}{\sqrt{\mathcal{E}_{reff}}} \quad (7)$$

Where,

$$\mathcal{E}_{eff} = \frac{\mathcal{E}_r+1}{2} + \frac{\mathcal{E}_r-1}{2}\left[\frac{1}{\sqrt{1+\frac{2h}{w}}}\right] \quad (8)$$

Step6: Feed calculations

Feed length $L_f = \frac{\lambda_g}{4}$ (9)



(a) (b) (c)

Figure 1. Proposed Antenna Design Structure

Initially evaluated conventional rectangular microstrip patch antenna dimensions at operating frequency are 27.66mm and 21.24mm using standard design equation (1) to equation (9). The proposed antenna comprises a compressed reduced ground plane at the bottom of the FR4 Substrate and the patch of the antenna is developed by subtracting a combination of two anti-symmetric half-Koch plus Minkowski curves. The dimension of each side of the Minkowski curve is 8.62mm and the 12.17mm height, 6.085mm base, and 13.6064mm side length of each Koch curve respectively. The feed is 3.1mm offset from the center of the patch width. Offset feed quarter wave feed line in conjunction with the compressed reduced ground is used for the improvement in the fractional bandwidth of the antenna from narrow bandwidth. The hybrid combination of fractal results in an additional band of 4.11GHz to 4.35GHz that is resonating at a frequency of 4.30GHz. Antenna utilizes a hybrid feeding technique a combination of shifted edge fed (offset) and inset fed is used for impedance matching at the designed frequency. The final optimized antenna structure is shown in Figure 1 and the dimensions of the antenna are represented in Table 1.

Table 1. Dimensions of the proposed antenna.

Parameter Name	Parameter Designation	Dimensions Values (in mm)
Substrate (FR-4) ε_r=4.4	Width: WSub Length: LSub Height: h	37.26 38.49 1.6
Ground (PEC)	Width: WGnd Length: LGnd	29.26 10.4
Patch	Width: WP Length: LP	27.66 21.24
50Ω Feed line	Feed width: Wf Feed length: Lf Offset distance from the center	3.0 12.45 3.1
Half-Koch Curves	Koch Height: hK Koch Side: SK Koch Base: bK	12.17 13.60647 6.085
Minikowski Curves	Edge: lM	8.62 (all dimensions)
Miscellaneous Dimensions	l_1 g	15.43 1

2.2 Effect of Offset Edge Feed Line

The effect of the feed line is displayed in Figure 2 and arranged in Table 2. It is observed from the table and figure that the antenna becomes dual band with two tuning frequencies and the first band becomes wideband instead of the narrow band as in the case of center edge feed by little offset (3.1mm shift towards half-Koch curve) position change in the feed line.

Table 2. Effect of type of feed line.

Feed Type	Tuning Freq. (GHz)	S_{11} (dB)	-10dB Bandwidth (GHz)	Gain (dBi)	Band
Edge Feed	2.50	-13.10	2.25-2.78	3.06	Narrow
Offset Feed	3.30, 4.30	-27.87, -20.60	2.23-3.80, 4.11-4.35	3.90, 3.05	Wide, Narrow

2.3 Effect of Ground Variation

Initially, the width of the ground (W_{Gnd}) and its length (L_{Gnd}) are equal to the width and length of the substrate. The hybrid half Koch-Minikowski fractal antenna with the complete ground has a tuning frequency of 5.60GHz with a narrow bandwidth. The ground length is reduced to quarter-wavelength (L_{Gnd}=12.45mm), this may result in dual narrow band reflection coefficients below -10dB. The ground length (without affecting the ground width) is further reduced to 10.4mm, this ascribed dual-band (one wide band 2.12-3.77GHz, and other narrow band 4.14-4.31GHz) below -10dB reflection coefficient with tuning frequencies at 2.59GHz and 4.25GHz respectively, but the gain in the second band is negative. The negative value of the gain and tuning of resonance frequency at 3.30GHz is improved by compressing the width of the ground by 8mm symmetrically. The effect of ground length variations and its width compressions are shown in Figure 3 and arranged in Table 3.

Table 3. Effect of ground length reduction and compression.

Ground Length, L_{Gnd}(mm)	Tuning Freq. (GHz)	$-S_{11}$ (dB)	-10dB Bandwidth (GHz)	Gain (dBi)

Complete ground (38.49mm)	5.60	16.38	5.55-5.66	0.91
$\frac{\lambda_g}{4}$ long ground (12.45mm)	2.90, 4.20	19.83, 11.31	2.74-3.12, 4.19-4.22	5.89, -1.32
Uncompressed Ground (W_{Gnd}=37.26mm) (L_{Gnd} =10.4mm)	2.59 4.25	21.79 20.23	2.12-3.77 4.14-4.31	4.32, -0.72
Compressed ground (W_{Gnd}=29.26mm) (L_{Gnd} =10.4mm)	3.30, 4.30	27.87, 20.60	2.23-3.80, 4.11-4.35	3.90, 3.05

2.4 Effect of Hybrid Fractal

Double anti-symmetric Minikowski-Minikowski curve cuts ascribed the wideband reflection coefficient below -10dB which is resonating at 3.20GHz with a gain of 3.20dBi. Double Koch-Koch symmetrical fractal curve cuts in the conventional rectangular patch result in a single wideband reflection coefficient with tuning at 3.20GHz. This also results in an improvement in the gain of 3.94dBi. Anti-symmetric half Koch-Koch Fractal curve in the rectangular patch decreases the resonating frequency towards the left 2.96GHz and slightly decreases the gain value 3.71dBi. A combination of two anti-symmetric half Koch curves and two Minkowski curve cuts results in dual wide bands (2.23-3.80GHz, and 4.11-4.35GHz) with resonant frequencies at 3.30GHz and 4.30GHz respectively. The effect of fractal curves has been experimented with on the conventional rectangular patch antenna. The effect of patch fractal curves is shown in Figure 4 and arranged in Table 4.

Table 4. Effect of Fractal Curves on Rectangular Antenna Patch.

Antenna Fractal Curve Type	Tuning Freq. (GHz)	$-S_{11}$ (dB)	-10 dB Bandwidth (GHz)	Gain (dBi)
Anti-symmetric Minikowski-Minikowski Fractal	3.2	34.08	2.34-3.67	3.20
Full Koch-Koch Fractal	3.2	22.41	2.27-3.80	3.94
Anti-symmetric Half Koch-Koch Fractal	2.96	18.01	2.37-3.84	3.71
Anti-symmetric Half Koch-Minkowski Fractal	3.30, 4.30	27.87, 20.60	2.23-3.80, 4.11-4.35	3.90, 3.05

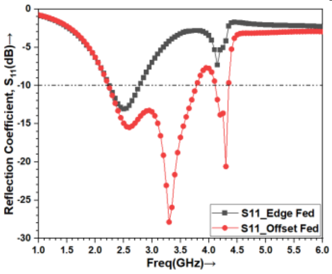


Figure 2. Offset feed Line Effect on Proposed Antenna

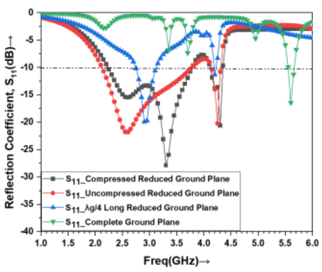


Figure 3. Effect of reduced ground and compressed ground length variations

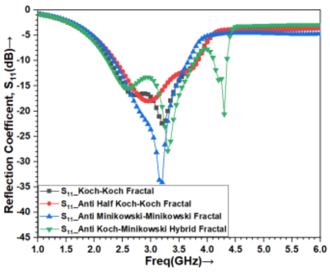


Figure 4. Effect of Fractal Curves Cut in the Rectangular Patch

2.5 Prototype of the Fabricated Antenna

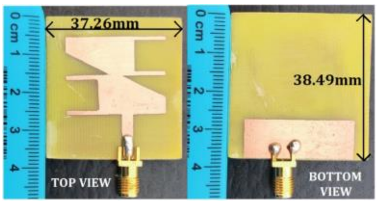


Figure 5. Antenna Prototype

The antenna is fabricated on a rectangular piece of low-cost FR4 substrate of size 37.26mm × 38.49mm × 1.6mm using photolithography and etching process as illustrated in Figure 5.

3 Results and Discussions

3.1 Antenna Reflection Coefficients Plot

The simulated and measured reflection coefficients of the proposed antenna are compared in Figure 6. This shows that the antenna has a dual-band nature with simulated resonance frequencies at 3.30 GHz and 4.30 GHz. It is also noticed from the graphs that both the simulated and measured reflection coefficients have two resonance frequencies. The measured resonance frequencies are right deviated from the simulated resonance frequencies by an amount of 200MHz and 400MHz, respectively with -10dB fractional bandwidth (FBW) of 47.57% (52% measured) and 5.58% (18.08% measured). The lowest reflection coefficient values at these frequencies are -27.87dB (-29.944dB measured) and -20.60 dB (-22.146dB). The resulting antenna is most suitable for Sub-6GHz, S-band (2.23GHz-3.80GHz), and C-band (4.11GHz-4.35GHz) applications. The measured reflection coefficient follows the shape of the simulated reflection coefficients. Therefore, the proposed dual-band fractal antenna is most suitable for general-purpose wireless applications like Wi-Fi, WLAN, Bluetooth, Industrial Society and Medical (ISM), Wi-Max, n40, n77, n78, n79 bands, etc. 5G mobile applications, and C-band Stellite and Radar applications.

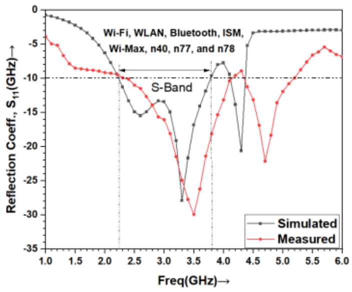
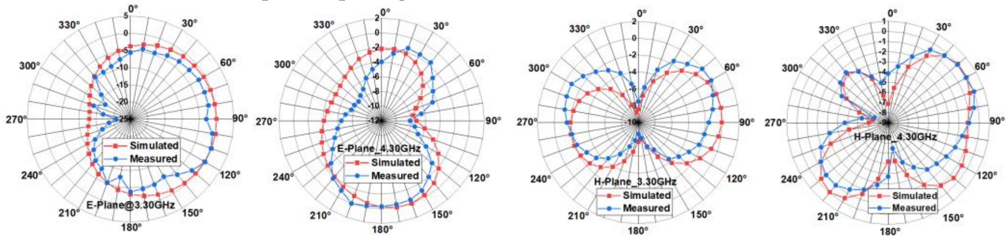


Figure 6. Reflection coefficients Plot of hybrid fractal antenna

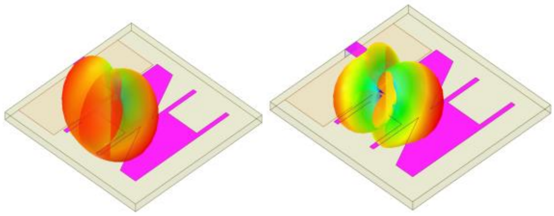
3.5 Antenna Radiation Patterns

The simulated and measured E-plane and H-plane gain radiation patterns of the antenna at resonance frequencies 3.30GHz and 4.30GHz are displayed in Figures 7(a) and 7(b). The E-plane radiation pattern maximum radiates along 90° at a frequency of 3.30GHz while along 270° direction at 4.30GHz as shown in Figure 7(a). The H-plane radiation pattern has main lobe radiation in a 90° direction while little less strong minor lobes in the backward direction. At a frequency of 4.30GHz H-plane pattern has two strong minor lobes as shown in Figure 7(b). The 3D-radiation pattern plots at two resonance frequencies 3.30GHz and 4.30GHz are represented in Figure 8 (a) and 8(b) respectively. The two simulated and measured gain patterns are found in approximations in shape and peak gain values.



(a) (b)

Figure 7. E-plane and H-plane Radiation Pattern Plots (a) 3.30GHz, and (b) 4.30GHz



(a) (b)

Figure 8. 3D-radiation Plots at resonant frequencies (a) 3.30GHz and (b) 4.30GHz

3.5 Resultant Parameters of the Proposed Antenna

All the resultant antenna parameters of the proposed hybrid half Koch-Minikowski fractal antenna are represented in Table 5.

Table 5. The resultant parameters of the antenna.

Antenna Parameter	Simulated Value	Measured Values
Resonant Frequency, f_r (GHz)	3.30	3.50
	4.30	4.70
Reflection Coefficients, S_{11}(dB)	-27.87	-29.944
	-20.60	-22.146
-10dB Fractional Bandwidth	2.23-3.80	2.30-4.15
(FBW) (GHz)	4.11-4.35	4.35-5.20
VSWR(<2)	2.21-3.80	2.31-4.20
	4.10-4.35	4.30-5.20
Lowest VSWR	1.10 at 3.30GHz	1.09 at 3.5GHz
	1.14 at 4.30GHz	1.12 at 4.70GHz
Polarization Type	Linear and Circular	Linear and Circular
Peak Gain (dBi)	3.90	4.12
Peak Radiation Efficiency	84.50%	-----

3.6 Antenna Axial Ratio (AR) Plot

Axial ratio elaborates on the orientation of the electric field vector concerning the magnetic field vector in other words the polarization information is hidden inside the axial ratio plot. The axial ratio lies greater than 3dB over the entire frequency band of interest except for a notch frequency range from 3.80GHz to 4.11GHz. This ascribed that the proposed antenna is dual-polarized (linearly as well as circularly polarized). The axial ratio plot of the proposed antenna is depicted in Figure 9. It is noticed from the graph that all the axial ratio values are greater than 3dB therefore the designed antenna behaves like a linearly polarized antenna except for the specified notch band.

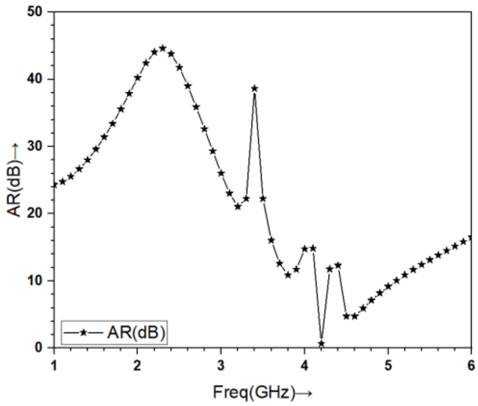
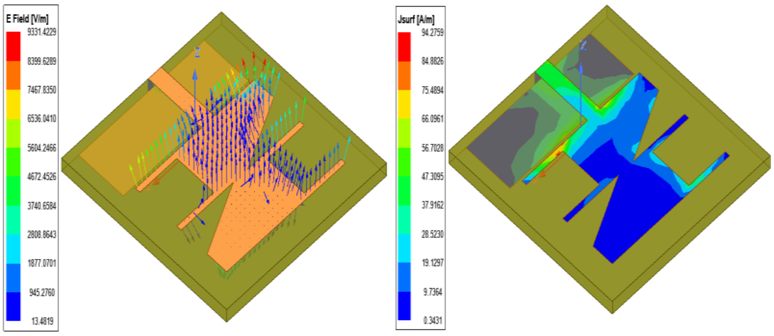


Figure 9. Axial ratio plot of the proposed antenna

3.7 Electric-Field Vector and Current Density Distribution



(a) (b)

Figure 10. (a) Electric field vector distribution, (b) Current density distribution

The electric field vector and Current density distributions of the anti-symmetric half Koch-Minikowski fractal antenna are represented in Figure 10. We have studied that in conventional rectangular patch antenna side arms radiations are negligibly small [7]. As fractal curves are applied at the side arms of the rectangular patch its electric field vectors and current density distribution are enhanced by a great amount as shown in Figures 10(a) and Figure 10(b).

3.8 Performance Comparison of Similarly Existing Antennas

The comparisons of the proposed design with the previously published work of the same type and design on the nearly same frequency at 2.4GHz have been listed in Table 6 in terms of antenna performance parameters. The proposed design is simple, compact, and easier to fabricate on double-etched layered PCB on a microstrip line. The Reflection coefficients and -10dB FBW of the proposed design are better than the existing designs as references [1-10]. The proposed Design is well resonated at dual-band at center frequencies 1.90GHz and 2.43GHz.

Table 6. Comparison of the proposed antenna with existing literature antennas.

Ref.	Ant. Shape and Feed Type	-10 dB BW (GHz)	f_r (GHz)	G (dBi)	Size (mm^2)
[12] 2018	Single Koch-Koch	2.51-2.90 7.74-10	2.77, 8.38	3.72,7.77	45× 38.92

[12] 2018	Single Koch-Minkowski	2.38-2.58, 7.56-10	2.46, 8.34	5.73, 5.62	45×38.92
[13] 2021	Ear shaped circular	1.22-47.5	7.4, 11.8, 17.2, 20.2, 24.8, 30.3, 38.6	between 0.2 to 9.7	40x45
[10] 2021	Tri-Rectangular Arms fractals	1.81-3.0	2.45	7.16	66.4x66.4
[14] 2018	Double Separate T-Shaped Slots	9-11 27-29 37-39	10/ 28/ 38	5.82 11.48 11.72	20 × 16.5
[15] 2013	Double U-shaped slots	3.49-3.74, 4.92-5.42	3.6/ 5.2	8.5, 8.6	50×50
[16] 2017	Rectangular Circular Fractal	2.73-2.88/ 5.69-5.92/ 7.73-7.88/ 8.07-8.14/ 8.53-8.91	2.8/ 5.8/ 7.8/ 8.0/ 8.72	1.07/ 2.53/ 5.94/ 6.2/ 9.3	55×35.5
[17] 2022	Spearhead-shaped monopole fractal antenna	3.28 -3.83	3.5	2.92	13×26
[18] 2018	Hybrid Minikowski-Koch Fractal	------	1.8/ 3.6/ 6.0/ 7.3/ 8.7/ 12.1	1.42/ 1.78/ 1.95/ 2.68/ 3.14/ 6.09	19×28
[19] 2019	Double separate Koch slots	2.3-2.45 4.4-4.6 7.3-8.1 9.2-9.7	2.4/ 4.48/ 7.57, 8.0/ 9.4	5.71 @ 2.37 GHz	37.29x29.06
This work	Hybrid Half Koch-Minikowski Fractal	2.23-3.80, 4.11-4.35	3.30/ 4.30	3.90/ 3.05	37.26×38.49

4 Conclusions

The article presents the design and fabrication of a dual-band (one wideband and another narrow band) antenna hybrid combination of two half Koch and two Minkowski fractal curves. The antenna is fed by the offset edge feeding technique and this results in circular polarization along with linear polarization. The reflection coefficient shows excellent impedance matching at the two resonant frequencies 3.30GHz and 4.30GHz. The antenna has radiation patterns with a peak gain of 3.90dBi at a design frequency of 3.30GHz. An upper-frequency band is controlled by the dimensions of the Koch and Minikowski curves. Thereby, the proposed design could be converted into a frequency-reconfigurable antenna in controllable and reversible by switching active elements like two PIN diodes or FET switch, etc. Since the measured reflection coefficient and radiation characteristics are in approximations with the simulated results, the proposed antenna is the most suitable candidate for the use of low-power MMIC/MIC transmitters and receivers for S-band and C-band wireless, satellite, RADAR, 5G mobile communication, and energy harvesting devices. It will also support some sub-6GHz 5G applications.

Acknowledgments. This work has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement H2020-MSCA-RISE-2018-EXPLOR-872897. This work is also funded by the FCT/MEC through national funds and when applicable co-financed by the ERDF, under the PT2020 Partnership Agreement under the UID/EEA/50008/2020 project. This publication has received funding from the European Union's Horizon Europe research and innovation program under grant agreement HE-MSCA-SE-6G-TERAFIT- 101131501. The authors would like to express their sincere thanks to our Honorable Vice-Chancellor, GK (DU), Haridwar, Uttarakhand, India for his motivation and encouragement towards the research and for providing the simulation and laboratory environment for conducting research works.

References

[1] Hariharasudhan, K. and Kumari, R. Metasurface loaded patch antenna for wi-fi applications. 2019 TEQIP III Sponsored International Conference on Microwave Integrated Circuits, Photonics and Wireless Networks (IMICPW); 22-24 May 2019; Tiruchirappalli, India. p.321-323.

[2] Karimah, S., Zulkifli, F.Y. and Rahardjo, E.T. Antenna design for femtocell LTE at frequency 2.3–2.4 GHz. In: Makassar International Conference on Electrical Engineering and Informatics (MICEEI); 26-30 November 2014; Makassar, Indonesia. IEEE, 26 March 2015, p. 50-53.

[3] Saravanan, M. and Rangachar, M.J.S. A narrowband corner slot patch antenna for 2.4 GHz wireless radio communications. Int J of Engg and Tech. 2016; 2149-2153.

[4] Palandöken, M., Baytöre, C. and Kaya, A. Compact WLAN monopole antenna with L-shaped strip line and spiral line loaded ring resonator. World Congress on Electrical Engg and Comp Systems and Sci. 2016; 139-1-139-6.

[5] Yadav, N. P. (2019). A four-element antenna array for amateur radio applications. National Journal of Antennas and Propagation. 2019; 1(1), 13-16.

[6] Samsuzzaman, M., Misran, N., Islam, M.T., Faruque, M.R.I. and ISLAM, T. Right-hand circularly polarized 2.40 GHz truncated corner patch antenna for small satellite application. Journal of Optoelectronics and Advanced Materials. 2019; 570- 576.

[7] Balanis, C. A. (2009). Antenna theory analysis and design. John Wiley and Sons, India, 2nd edition, reprint 2009. ISBN 978-81-265-1393-2.

[8] Werfelli, H., Tayari, K., Chaoui, M., Lahiani, M., Ghariani, H. Design of rectangular microstrip patch antenna. In 2nd International Conference on Advanced Technologies for Signal and Image Processing (ATSIP); 21-23 March 2016; IEEE, Monastir, Tunisia. p.798-803.

[9] Jamlos, M.F., Rahim, R.A., Othman, H., Jusoh, M., Ahmad, Z.A., Romli, M.A., and Salimi, M.N. Dual frequencies of half-monopole antenna for WiMAX and Wi-Fi application. IEEE Symposium on Wireless Technology and Applications (ISWTA); 23-26 September, 2012; IEEE, Bandung, Indonesia, 06 December 2012. p.130-133.

[10] Varshney, A., Cholake, N., and Sharma, V. Low-cost ELC-UWB fan-shaped antenna using parasitic SRR triplet for ISM band and PCS applications. International Journal of Electronics Letters. 2021; 10, 391-402.

[11] Varshney, A., Neebha, T.M., Sharma, V., Jency, J.G., and Andrushia, A.D. dodecagon-shaped frequency reconfigurable antenna practically loaded with 3-delta structures for ISM band and wireless applications. IETE Journal of Research. 2022; 1-13.

[12] Sharma, N.; Sharma, V. A design of Microstrip Patch Antenna using the hybrid fractal slot for wideband applications. AIN Shams Engineering Journal 2018; 9, 2491-2497.

[13] Balani, W., Sarvagya, M., Samasgikar, A. Ali, T., Kumar, P., Design, and Analysis of Super Wideband Antenna for Microwave Applications. Sensors. 2021; 21, 477.

[14] Abdelaziz, A., Ehab, K., Hamad, I. Design of a compact high gain microstrip patch antenna for tri-band 5 g wireless communication. Frequenz. 2018; 73, 45-52.

[15] Liu, S., Qi, S., Wu, W., Fang, D. G. Single-fed dual-band dual-polarized U-slot patch antenna. 2013 IEEE MTT-S International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-BIO);09-10 December 2013; Singapore. IEEE Xplore; 06 March 2014. P. 1-3.

[16] Kaur, N., Sharma, N. Designing of slotted microstrip patch antenna using Inset Cut line feed for S, C, and X-band applications. Internat J of Electr Engg R. 2017; 9(7), 957-969.

[17] Varshney, A., Sharma, V., Neebha, M., and Kumar, R. Printed Antennas. 1st. Boca Raton, CRC Press; 2022. Chapter 14, A compact low-cost impedance transformer-fed wideband monopole antenna for Wi-MAX N78-band and wireless applications; p.315-328.

[18] Bangi, I. S., and Sivia, J. S. A compact hybrid fractal antenna using Koch and Minkowski curves. 2018 IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON); 01-03, November 2018; Vancouver, BC, Canada. IEEE Xplore **:** 17 January 2019. P. 838-843.

[19] Fonseca, D., Pereira F., Ulysses, Vitor, R. C. Study of Patch Antennas with Koch Curve Form Slots. J of Microw, Optoelectr, and Electromag Appl. 2019; 18(3), 399-407.