Meander and Koch Hybrid Fractal Curve Based Dual Hexagonal Radiating Patch Antenna for Quad Band Wireless Applications

Jagtar Singh Sivia1 · Sumeet Singh Bhatia1

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Abstract
A unique dual hexagonal-shaped radiating patch design with hybrid fractal curves (Meander and Koch) is presented for quad-band wireless applications. Initially, the antenna from 0th to 2nd iteration of hybrid fractal curves with PGP (Partial Ground Plane) is designed and investigated. Further, to get better results of the designed antenna in respect of Bandwidth (BW) and coefficient of reflection these hybrid curves are superimposed on the limited ground plane of 1st and 2nd iteration of the antenna and the generated antennas are designated as Antenna–1 and Antenna–2. A comparison between both the antennas has been made and it is observed that Antenna–2 shows better results in respect of improved BW and coefficient of reflection. The proposed antenna exhibits four resonant frequency bands 1.6, 4.8, 6.9, and 8.8 GHz with improved corresponding impedance BW of 2.09, 1.36, 0.86, and 1.51 GHz. The designed antenna is simulated and made on FR4 glass epoxy substrate with an overall size of 20×40×1.6 mm3. The fabricated proposed antenna is tested experimentally for the authentication of simulated results with experimental results and these are compatible with each other. The other performance indicators like radiation pattern, peak realized gain, and radiation efficiency are also determined for the proposed Hybrid Fractal Antenna (HFA) and all are found satisfactory. Due to the improved operational parameters, the designed HFA can be considered as a suitable applicant for distinct wireless applications in anticipated operational frequency ranges.

Keywords Koch · Meander · Hybrid fractal · Patch antenna · Wi-MAX

Jagtar Singh Sivia
jagtarsivian@gmail.com

Sumeet Singh Bhatia
bhatia8@gmail.com

1 Department of Electronics and Communication Engineering, Yadavindra College of Engineering and Technology, Punjabi University, Guru Kashi Campus, Talwandi Sabo, Bathinda, Punjab, India
1 Introduction

In the recent moving age of wireless communication, numerous amendments are done in the field of antennas by eminent researchers to encounter the existing need of the marketplace. Basically, the antenna is a prime requirement of the various gadgets that are used by the individuals in their life, such as smartphones, laptops, smart televisions, i-pads, toys, wireless gaming equipment, etc. There is an excess of literature that has been presented that is linked to patch antennas but the fractal antenna has made its exceptional identity in the family of antennas because of its unusual features and capability to inhabit the huge surface area in restricted space [1, 2]. The fractal was first presented in 1975 by B. Mandelbrot on naturals fractals [3, 4]. Fractals are complicated in shape which occurs in nature or can be generated by means of IFS (Iterative Function System) [5, 6]. Fractals are based on distinct properties such as fractional proportions, space-filling, immeasurable complexity, and self–similarity due to which they exhibit wideband and multiband characteristics [7–9]. The utmost major properties of fractal shapes are self–similarity and space-filling. Space-filling property condenses of the overall antenna size known as miniaturization of antenna by refining the relative permittivity and permeability of substrate material [10, 11]. Whereas, another important property is beneficial to achieve the wideband/multiband characteristics [12, 13]. The shapes which are most commonly used in generating the fractal antennas are Koch [14–16], Minkowski [17–19], Sierpinski Gasket and Carpet [20–22], Hilbert [23–25], Giuseppe Peano [26–28], Meander [29–31], etc. All the discussed fractal shapes have their inimitable implication in the design of antennas for definite wireless standards. Antenna based on distinct fractal shapes is not able to attain multiband and wideband characteristics deprived of negotiating the operation of the antenna. By keeping more attention on the problem, numerous researchers have attached above mentioned shapes together to project the different antennas for various wireless standards. These invented shapes are known as hybrid shapes and thus antennas obtained by applying these shapes are denoted as HFA (Hybrid Fractal Antenna). This can be generated by employing the different amalgamations as Koch-Koch, Meander-Meander, Koch-Meander, Koch-Sierpinski carpet/gasket, Sierpinski carpet/gasket-Giuseppe Peano, etc.

In this document, a unique design of dual hexagonal patch is designed and the hybrid fractal shape of (Meander and Koch) has been superimposed on the construction of radiating patch to advance the presentation of the antenna in respect of coefficient of reflection, BW, and gain. Further, the hybrid curve has also been introduced on the PGP of the proposed shape of the antenna to attain wideband characteristics. The final shape of the proposed HFA has been made up and tested for the authentication of simulated and experimental results. The juxtaposition of these results shows that they are congruent with each other.

The versatile mathematical tool called IFS is used to design the required hybrid curve as shown in Fig. 1. In this design, two types of fractal curves are fused together such as the Meander fractal curve with indentation angle \( \theta = 90^\circ \) and Koch fractal curve with angle \( \theta = 60^\circ \) and designated as the generator curve. This generator can be used as the base geometry to obtain the next iterations of similar shapes. The generator curve comprises seven segments. For achieving the required fractal curve, the design process is started with the straight line, called an initiator with \( n = 0 \) and generator curve with \( n = 1 \). The length of the initiator (straight line) is equal to the radius of the hexagonal-shaped radiating patch (\( P_1/R_1/R_2 = 7.2 \) mm). The same procedure is repetitive up to the 2nd iteration with \( n = 2 \).
The final geometry has been obtained by duplication of the reduced form of the generator curve on the seven segments of the generator itself. Due to the self-similarity property, the total length ‘l’ of the final curve is given by:

$$l = h\left(\frac{N}{r}\right)^n = 7.2 \left(\frac{7}{4}\right) = 22.05\text{mm}$$

(1)

Here ‘r’ represents the number of each segment divided on iteration, ‘N’ denotes the number of segments, ‘n’ indicates the number of iterations and ‘h’ represents the height of the curve.

The process can be repetitive for gaining the further iterations of the anticipated hybrid fractal curve, for the self-similarity index (D), deliberate by using the following equation:

$$D = \frac{\log(N)}{\log(r)} = \frac{\log(7)}{\log(4)} = 1.4036$$

(2)

The Koch and Meander curve is designed and merged together to attain desired hybrid fractal curve. Further, this designed hybrid curve [0th iteration (n=0) and 1st iteration (n=1)] is integrated with the double hexagonal shaped radiating patch as illustrated in Fig. 2a and b. The 2nd iteration (n=2) of the hybrid curve on double hexagonal shaped radiating patch as shown in Fig. 2c is designated as the desired geometry (2nd iteration) of the proposed antenna.

2 Antenna Design

2.1 HFA Design Evolution

This manuscript presents the design of a unique dual hexagonal patch antenna loaded with Koch and Meander hybrid fractal curve for quad-band wireless applications. The initial design of the antenna begins with designing the hexagonal radiating patch and its radius is evaluated with the subsequent equations [32, 33] by using different designing parameters. Further, the generated hexagonal patch is copied and attached to the upper side of another hexagonal patch to obtain the desired dual hexagonal radiating patch shape as reported in
Fig. 2a. A partial ground plane and a 50Ω transmission line feed have been used to excite the designed radiating patch and to obtain the proper impedance matching characteristics. The HFA is designed and investigated by employing the simulator called Ansys HFSS V13 is based on the finite element method.

Further, the 1st iteration of the hybrid fractal curve (Koch and Meander) is engraved from the outer sides of the dual hexagonal-shaped radiating patch as previously designed to acquire the 1st iteration of the proposed antenna. These designs of the hybrid fractal curves are inspired and taken from [34, 35] and the process of designing and hybridization of these curves are simply omitted here for the sake of easiness. Similarly, the 2nd iteration of these curves is introduced on the dual hexagonal-shaped patch to attain the 2nd iteration of the designed HFA as depicted in Fig. 2c. Parametric dimensions of the designed antenna are tabulated in Table 1. The assessment of the simulated coefficient of reflection response with respect to resonant frequency for every designed iteration is depicted in Fig. 3.

It can be observed from Fig. 3, that the 0th iteration of the antenna exhibits a single frequency band at 6.1 GHz with the corresponding coefficient of reflection of −12.24 dB and a BW of 770 MHz (5.68–6.45 GHz). Whereas, 1st iteration of the antenna reveals one more frequency band as compared to the 0th iteration and displays a frequency band at 1.7 (−12.28 dB) and 5.2 GHz (−17.94 dB) with a −10 dB impedance BW of 1.07 GHz.
Finally, 2nd iteration of the antenna reports the dual-frequency band at 1.7 GHz and 5.0 GHz with a coefficient of reflection of −14.40 dB and −20.26 dB respectively. This antenna reveals the BW of 1.29 GHz (1.31–2.6 GHz) and 1.01 GHz (4.56–5.57 GHz). It is evident from the above discussion that modification in the shape of the designed radiating patch plays a vital role in improving the antenna operational parameters in respect of coefficient of reflection, BW, and number of frequency bands. In this sub-section, the hybrid fractal curves up to 2nd iteration are superimposed on the dual hexagonal-shaped radiating patch to investigate the operation of the antenna. Further, the 1st and 2nd iteration of the hybrid curve is employed on the PGP in the next sub-section, which should lead to the enhancement of resonant frequency bands and better impedance matching characteristics.

### 2.2 Effects of Hybrid Fractal Curve on Partial Ground Plane (PGP)

In this sub-section the 1st iteration of the hybrid fractal curve is employed in the PGP of the 1st iteration of the antenna and designated as Antenna–1 as shown in Fig. 4a. Similarly, the 2nd iteration of the hybrid curve is employed on the PGP of the 2nd iteration of the antenna and is called Antenna–2 (proposed) as illustrated in Fig. 4b. The coefficient of reflection response of these antennas is compared in Fig. 5. It can be observed from Fig. 5, that the modification in PGP reveals the quad-band frequency response in the required frequency range. After analyzing the frequency response of Antenna–1, it can be anticipated that it resonates at 1.6, 5.1, 7.4, and 9.6 GHz with a corresponding coefficient of reflection of −14.71, −29.66, −14.91, and −11.58 dB. Whereas, Antenna–2 reveals the resonance points at 1.6, 4.8, 6.9, and 8.8 GHz with the corresponding coefficient of reflection of −19.45, −35.92, -23.29, and −16.27 dB. It is also pragmatic that the Antenna–2

![Fig. 3 Coefficient of reflection versus frequency plot of HFA](image-url)

| Parameter | S₁ | S₂ | R₁ | R₂ | T₁ | F₁ | F₂ | G₁ |
|-----------|----|----|----|----|----|----|----|----|
| Size (mm) | 20 | 40 | 7.2 | 7.2 | 0.55 | 14.05 | 1.0 | 13.5 |
(proposed) divulges enhanced coefficient of reflection and BW at all the frequency points and the resonant frequency of second, third, and fourth band shifts towards the lower side from also shifts from 5.1 to 4.8 GHz, 7.4 to 6.9 GHz, and 9.6 to 8.8 GHz which also helps in reducing the overall size of the antenna. The simulated results of the antenna (Antenna–1 and 2) with modified PGP are compared in Table 2 for better understanding. Due to the enhanced operation, Antenna–2 acts as a final proposed shape of the antenna and has been fabricated for the authentication of obtained results. The fabricated prototype and the comparison of measured results for the final shape of the proposed antenna are discussed in detail in the next section.

The current distribution on the plane of the patch and modified ground plane of the final structure of the designed antenna at operational resonant frequency points are plotted and expounded in Fig. 6. It can be predicted from Fig. 6a that current is concerted on the PGP loaded with a hybrid fractal curve in conjunction with dual hexagonal-shaped hybrid
radiating fractal patch and microstrip transmission line, due to which proposed antenna displays enhanced coefficient of reflection and BW at 1.6 GHz in association with the Antenna –1. Further, at other resonant frequency points such as 4.8 and 6.9 GHz, the current is largely concerted on the fractal curve edges of the radiating patch as well as on the transmission line, which supports the shifting of frequency bands and improvement in coefficient of reflection. Finally, at the final frequency point as 8.8 GHz, the large current will get saturated at the lower edges of radiating patch and at the ground plane in conjunction with line feed which helps to achieve the upgraded coefficient of reflection and BW up to 1.51 GHz in comparison to other structures of the antenna (Antenna–1) which exhibit only 0.50 GHz BW at the last frequency band.

Fig. 6 Current distribution plots of the HFA at; a 1.6, b 4.8, c 6.9 and d 8.8 GHz frequency points

Table 2 A Comparison of proposed HFA with existing antennas of same category

| Reference | Fractal curves                  | Size of antenna (mm²) | Resonant frequencies (GHz) | Maximum gain (dB) |
|-----------|---------------------------------|----------------------|----------------------------|-------------------|
| [36]      | Sierpinski and Meander         | 700x400              | 0.89/1.85/2.04             | 2.1               |
| [37]      | Koch and Cantor                | 25x66                | 1.9/3.15                   | 4.78              |
| [38]      | Koch and Minkowski             | 45x38.92             | 4.46/8.78                  | 5.73              |
| [39]      | Koch and Minkowski             | 39.4x48.4            | 2.45/3.85/4.45             | 6.8               |
| [40]      | Sierpinski Carpet and Gasket   | 59x29                | 2.36/4.7                   | 6.1               |
| [41]      | Sierpinski gasket and Meander  | 400x400              | 0.925/1.85/2.045           | –                 |
| [42]      | Giuseppe Peano and Cantor      | 34x34                | 2.44/5.81                  | 10.19             |
| This work | Meander and Koch               | 20x40                | 1.6/4.8/6.9/8.8            | 6.85              |
3 Manufactured Model and Test Results

This section deals with the made-up model of the proposed antenna together with the comparison of simulated and measured results of various operational indicators. The fabricated structure of the antenna has been delineated in Fig. 7 and the assessment of simulated and measured coefficient of reflection are depicted in Fig. 8. It can be seen in Fig. 8, that the measured antenna exhibit all the frequency bands almost similar to the resonant points revealed by the simulated antenna. So, we can say that both the results (simulated and measured) are in a good match with each other. But, small discrepancies have been reported among the simulated and measured results which may have arisen as a result of the manufacturing tolerance such as soldering bumps of SMA connector as well as inappropriate etching of copper and some variations in the physical dimension of the fabricated structure.
The measured proposed antenna displays the operational frequency ranges from 1.10 to 3.24 GHz, 3.93–5.24 GHz, 6.57–7.29 GHz, and 8.12–9.72 GHz with corresponding impedance BW of 2.14, 1.31, 0.72, 1.60 GHz. From these measured results, it is evident that proposed HFA can be used for distinct wireless standards such as 1800 MHz 2G spectrum of GSM band (1.71–1.88 GHz), Aircraft Surveillance (1.09 GHz), 3G Cellular Communication Mobile Uplink (1.90–1.98 GHz), Advance Wireless Services (2.11–2.15 GHz), LTE 2300/LTE 2500 (2.3–2.4 GHz/2.5–2.69 GHz), RFID (2.4 GHz), Wi-Fi (2.4–2.485 GHz), Bluetooth (2.4 GHz), WiMAX (3.3–3.7 GHz), mobile/fixed satellite navigation (6.61–7.04 GHz, 8.175–8.215 GHz) and aeronautical and radio navigation (9.0–9.5 GHz).

Graphical illustration of the variation in the field strength of radio waves in 2D and 3D space has been specified by using the radiation pattern of the antenna. As the patch antennas are radiate normally to the surface of the metallic radiating element, so these patterns are shown in the rectilinear or polar form with a decibel (dB) strength scale. The simulated and measured radiation patterns in E and H-plane at distinct resonant frequency points are delineated in Fig. 9. Proposed HFA reveals nearly bidirectional in E-plane and completely Omni-directional pattern in H-plane at operative frequency bands, which clearly postulates that the proposed antenna is an appropriate candidate for multiband wireless applications.

Peak realized gain and radiation efficiency versus frequency are represented in Fig. 10 in the anticipated frequency ranges. This evidently displays that the measured and simulated gain responses are in reasonable congruent with each other. It can also be reported that the gain of the proposed antenna varies between 1.0–4.87 dB, 4.62–5.28 dB, 4.98–6.85 dB, and 4.75–6.28 dB in the attained operative frequency ranges. Also, the radiation efficiency of the proposed antenna varies from 0.87% to 0.79% in the first frequency range and is almost constant between 0.78–0.80% in the other three operational frequency ranges.

The comparison of the proposed HFA has been made with the existing antennas of the same category and illustrated in Table 2 for better understanding. It is evident from

![Fig. 9 Normalized radiation pattern of the HFA in E and H-plane at (a) 1.6, (b) 4.8, (c) 6.9 and (d) 8.8 GHz resonant frequency points](image-url)
Table 2, that the proposed HFA is compact in size and exhibits more frequency bands as compared to the other reported antennas. It has also been observed that HFA deliberated in [42] exhibits more gain as demonstrated by proposed HFA, but it projects less number of frequency bands as well as larger in size, in comparison to it. Thus, giving reliable vision to the above conversation, it can be anticipated that the proposed HFA is best amongst the existing HFAs represented in state of art of literature.

4 Conclusion

A quad-band HFA using Meander and Koch fractal curves on dual hexagonal-shaped radiating patch is presented in this manuscript. Three iterations of hybrid fractal curves are superimposed and excited by using 50Ω transmission line feed as well as a partial ground plane. Further, these curves are applied on a partial ground plane to improve the BW and coefficient of reflection of the designed antenna. The proposed antenna with the 2nd iteration of the curve on the partial ground plane and radiating patch reveals four resonant frequency bands 1.6, 4.8, 6.9, and 8.8 GHz with an improved coefficient of reflection and impedance BW. The final design of the antenna is manufactured in the lab and tested experimentally, also the results are compared with simulated results and found incongruent with each other. Due to the enhanced operation of the proposed HFA, it can be a suitable candidate for district wireless applications such as 1800 MHz 2G spectrum of GSM band, Aircraft Surveillance, 3G Cellular Communication Mobile Uplink, Advance Wireless Services, LTE 2300/LTE 2500, RFID, Wi-Fi, Bluetooth, WiMAX, mobile/fixed satellite navigation and aeronautical and radio navigation.

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Declarations

Conflict of interest  The authors have no conflicts of interest to declare that are relevant to the content of this article.

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Jagtar Singh Sivia  born in Bathinda, Punjab in 1976. He has received his B.Tech degree from Punjab Technical University, Jalandhar, Punjab in Electrical and Electronics Communication Engineering in 1999 and he had obtained his master degree from Punjab Technical University, Jalandher in 2005. He had received his Ph.D degree from Sant Longowal Institute of Engineering and Technology, Longowal, Punjab. Currently, He is a professor in Electronics and Communication Section at Yadavindra College of Engineering, Off-Campus of Punjabi University, Patiala, Punjab, India. He has published more than 60 papers in several International Journals and International and National Conferences. His main interests are in Neural Networks, Electromagnetic Waves, Genetic Algorithms, Antenna System Engineering. Mr. Sivia is a member of Institution Engineers in India, Indian Society of Technical Education and International Association of Engineers.

Sumeet Singh Bhatia  was born at Sri Karanpur, Rajasthan in 1990. He received Bachelor of Technology degree in Electronics and Communication Engineering from Amritsar College of Engineering and Technology, Amritsar, Punjab, India in 2012. He completed his Master of Technology degree in Electronics and Communication Engineering from Yadavindra College of Engineering, Guru Kashi Campus, Punjabi University, Talwandi Sabo, Bathinda, Punjab, India in 2015. He is reviewer of the various esteemed journals like International Journal of Electronics, Electronics Letter (Taylor and Francis), Progress In Electromagnetic Research (PIER) and International Journal of Sensors, Wireless Communications and Control (Bentham Science Publishers). More than 25 research papers in various International Journals and referred conferences goes into his credit. His research interest lies in the areas of microstrip, fractal and Ultra-wideband antennas.