

Emerging Perspectives on Multiband Fractal and Hybrid Fractal Antennas for Wireless Applications: A Comprehensive Analysis

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Abstract: In the rapidly evolving field of wireless communications, the demand for compact, efficient, and versatile antenna systems has led to significant interest in multiband hybrid fractal antennas. This paper presents a brief overview to the basic fractal structures and their utilization to develop hybrid fractal patch antenna design. The key interest areas are multiband behaviour, acceptable return loss, voltage standing wave ratio, gain and reduced complexity. Many studies have simulated and examined the antenna using the Finite-Difference Time-Domain (FDTD) and Finite Element Method (FEM) based techniques. Various antenna performance parameters such as return loss, resonant frequency, bandwidth, and gain are observed and the findings of several articles have been presented. The compact size, multiband/wideband features, and extensive utility in wireless applications make the fractal antenna a promising field of study. These antennas are so popular because of their electrically vast construction, which neatly folds into small spaces.

Keywords: *Microstrip Patch Antenna, Fractal Structure, Hybrid Fractals, Multiband, Return Loss, Iterated function system (IFS)*

INTRODUCTION

In the dynamic field of wireless communication, the demand for smaller, more versatile devices that support multiple wireless standards has become increasingly prevalent. In order to meet this need, multiband antennas are essential since they allow the RF front-end to be as small as possible while yet supporting a variety of wireless protocols [1-4]. Antenna is an incredible part of telecommunication industry [5-7]. Communication devices nowadays are devised to be able to work on different wireless standards thus requiring operational characteristics compatible with multiple frequencies. Technological advancements in wireless applications have encouraged the improvisation of antennas to large extent. Appreciable enhancement has been witnessed in last few decades in the development of antennas being employed for wireless and multiband applications in communication system [8-10]. Multiband antennas are designed to operate across multiple frequency bands, allowing them to support various wireless standards such as GSM, CDMA, LTE, Wi-Fi, Bluetooth, and more [11-13].

This versatility together with space efficiency is essential for modern devices that need to connect to diverse networks without the need for multiple dedicated antennas. Microstrip patch antennas are widely used in current communication systems because of their amazing features, which include ease of manufacture, low cost, tiny size, and light weight [14-16].

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1.1. Microstrip Patch Antennas

Microstrip patch antennas have completely changed the wireless sector because of its structural simplicity and ease of production. The demand for microstrip patch antennas has consequently experienced gigantic increase and continues to grow [17-18]. Furthermore, they are easily programmable to function in dual or circular polarization, as well as multi-band applications [19-21]. Compact, dependable, efficient, and multiband antennas are in increasing demand due to rising data rates and high-speed wireless applications [22-24]. The idea of microstrip as radiator was first proposed by Deschamps in 1953 [25].

1.2. Fundamentals of Fractal Antennas

Microstrip patch antennas are essentially narrowband devices. The ratio of the operating wavelength to the antenna size has a significant impact on their behaviour [26-28]. This indicates that when the operating frequency is changed, the primary antenna characteristics such as gain, power distribution, impedance, radiation patterns will experience significant fluctuations for a constant antenna size [29-31]. Moreover, there is a certain limit on size minimization of an antenna, usually of the order of a quarter wavelength. In this regard, the fractal architecture of antennas can aid in solving the mentioned issue by providing diverse range of geometric forms with astounding characteristics [32-34]. In order to achieve multiband properties [35], which is not possible with a traditional microstrip patch antenna, fractal antenna geometry is mostly employed [36-39].

Mandelbrot [40] offered the following definition of Fractals: “A fractal is by definition a set for which the Hausdorff dimension strictly exceeds the topological dimension”. This definition was later retracted and replaced with: “A fractal is a shape made of parts similar to the whole in some way”. A fractal structure is, thus, one that exhibits symmetry across size, self-similarity at different magnifications, and small-scale replication of the object's overall structure in every section. The self-resemblance and plane-filling properties of fractal geometries are frequently associated with their frequency features, such as their ability to operate at many frequencies in electromagnetic devices [41-42] and by using space-filling and self-similarity features, fractal geometries may generate longer current paths in constrained spaces [43-45]. This improves the antenna's properties, maintaining a smaller antenna size and radiation patterns that are amazingly comparable to those of their bigger counterparts. Fractals are mostly used in antenna engineering to broaden the perspective on antenna design and move away from Euclidean geometry, which holds that an antenna's closed area is proportionate to its perimeter [46-48]. Fractal dimensions are characterized by a fractal similarity parameter D as given in equation (1.1) below [49].

$$D = \frac{\log(L)}{\log(r)} \quad (1.1)$$

where

L is total length before performing fractalization

& r is number of segment divisions.

1.3. Types of Fractal Geometries

Sierpinski Gasket: Sierpinski gasket fractal structure and its properties are described by Polish Mathematician, Wacklaw Sierpinski in 1915. It is created by repeatedly eliminating inverted equilateral triangles from an equilateral triangle as shown in fig. 1 below [50]. A triangle from middle of equilateral triangle is removed in first iteration. The Sierpinski gasket is referred as self-similar geometry because the left three triangles after first iteration are precise replicas of initial triangle. This antenna's self-similar current distribution demonstrates the multi-band properties [51]. The antenna's multi-band nature may be managed by adjusting its geometry,

and by altering the flare angle, one can modify the antenna's band characteristics [52]. The Sierpinski gasket triangle's form is determined by four factors: the height of the triangle 'h', the scaling factor 'S_f', the flare angle 'h', and number of iterations, 'n'.

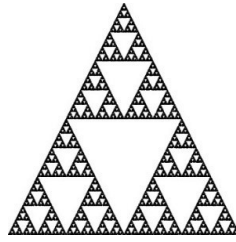


Fig. 1. Sierpinski gasket [51]

Sierpinski Carpet: In Sierpinski carpet fractal structure, the rectangular patch is used to derive the desired geometry. The center of the primary rectangle is subtracted from the one-third-size rectangle. Several iterations of this procedure are performed to get the desired geometry. As shown in fig. 2, this antenna is designed by a series of iterations utilizing the self-similarity feature of fractal antenna [53].

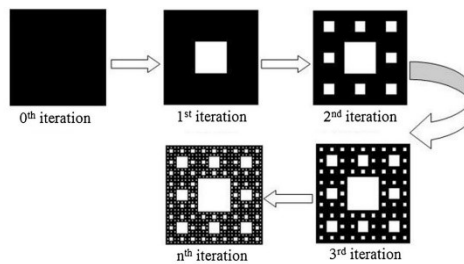


Fig. 2. Generation of Sierpinski carpet [53]

Koch Curve: The Koch curve is a mathematically proven fractal shape that demonstrates self-similarity at different scales. It gets its name from Swedish mathematician Helge von Koch who developed this geometry. The construction of the Koch curve involves iteratively adding smaller segments to a starting line. Step by step procedure to construct the Koch Curve is given below:

- Start with a straight-line segment.
- Divide the line into three equal parts.
- Then triangular shape is formed when centre portion of the straight line is bent with flare angle 60 degree resulting in formation of equilateral triangle [54].
- Repeat the process for each of the four-line segments created in the previous step as shown in fig. 3 below.

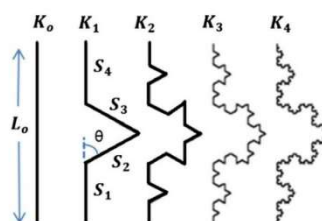


Fig. 3. Four iterations of Koch fractal [54]

Minkowski Curve: Minkowski geometry extends the principles of Euclidean geometry into the realm of spacetime [55]. A Minkowski fractal is a type of geometric fractal that is

constructed using a recursive process based on the Minkowski operation, which involves adding or subtracting geometric shapes at various scales. The resulting structure exhibits self-similarity at different levels of magnification as depicted in fig. 4.

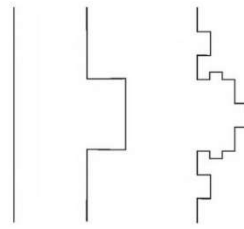


Fig. 4. Generation of Minkowski fractal up to 2nd iteration [56]

Cantor Set: A typical example of a fractal structure that exhibits self-similarity and is generated through a simple iterative process is a Cantor set. We can generate a Cantor set by following below mentioned procedure:

- Begin with a line segment. This segment represents the "zeroth iteration" of the Cantor set.
- Divide the line segment into three equal parts.
- Out of three parts, remove the middle part of the line segment.
- Repeat steps 2 and 3 for each of the remaining line segments (the two outer segments resulting from the previous step).
- Continue this process of removing the middle third of each remaining line segment infinitely at each iteration.

After performing several iterations, Cantor set is designed as shown in fig. 5, which is a fractal with some interesting properties like it is self-similar, meaning that each portion of the set resembles the whole set and it is perfect disconnected, compact metric among the fractal structures [57].



Fig. 5. Various iterations of Cantor set fractal [57]

1.4. Iterated Function System

An iterated function system (IFS) in fractal geometry is used to produce intricate and self-similar patterns by repeatedly applying a series of affine transformations [58-59]. Fractal antennas, being a subset of fractal geometry, can be designed using IFS techniques to achieve certain desired characteristics such as multiband operation, miniaturization, and wide-angle radiation patterns. By utilizing iterated function systems, fractal antennas can be created with intricate structures and desired electromagnetic properties, making them suitable for various wireless communication and sensing applications.

1.5. Design and Simulation

Designing and simulating a fractal antenna involves several steps including understanding fractal geometries, choosing a specific fractal type, using appropriate software for design and simulation, and analysing the performance of the antenna. The brief overview of each process is as follows:

- a) Choose a Fractal Geometry: Fractal antennas are typically based on self-similar geometric shapes like fractal curves or surfaces. Common examples include the Koch curve, Sierpinski gasket, Menger sponge, or various iterations of the Mandelbrot set [60].
- b) Define Affine Transformations: Affine transformations involve translations, rotations, scaling, and shearing. Each transformation is represented by a matrix that describes how points in the original fractal pattern are mapped to new locations. These transformations are applied iteratively to generate the fractal antenna structure [61].
- c) Iterate Transformations: Apply the chosen set of affine transformations repeatedly to each point in the fractal pattern. As the iterations progress, the antenna structure becomes more complex and self-similar [62].
- d) Adjust Parameters for Antenna Performance: During the design process, parameters such as the scaling factor, rotation angle, and translation vectors can be adjusted to achieve specific antenna performance characteristics. For instance, tweaking these parameters can optimize the antenna for certain frequency bands or radiation patterns [63].
- e) Simulation and Optimization: Once the fractal antenna structure is designed using the IFS method, simulation can be done using various electromagnetic simulation software such as High Frequency Structure Simulator (HFSS), CST Microwave Studio etc. Simulation results can help evaluate the antenna's performance metrics like impedance matching, radiation efficiency, gain, and bandwidth. Further optimization may be performed to fine-tune the antenna design based on simulation results.

1.6. Prototype and Testing

After finalizing the design, the prototype and testing process of a fractal antenna design involves several stages. First, the design is fabricated using materials such as copper on a suitable substrate, employing methods like PCB etching or photolithography. Once the prototype is ready, it undergoes testing with equipment such as a Vector Network Analyzer (VNA) for S-parameter measurements, and an anechoic chamber for radiation pattern and gain analysis [64]. The key parameters measured include return loss (s_{11}), bandwidth, radiation pattern, gain, and VSWR [65]. These results are then compared with simulation data to identify any discrepancies [66-67]. The process is iterative, involving adjustments to optimize the antenna's performance based on the measurement outcomes.

2. INVESTIGATIONS ON ADVANCEMENT IN FRACTAL ANTENNAS

J. Malik et al. [68] designed a proximity feed, multi-layered, dual band complementary Sierpinski fractal antenna construction with bandwidth of 100 and 150 MHz at 3.5 and 5.8 GHz respectively. The overall design scales are $25 \times 35 \times 1.6 \text{ mm}^3$ and substrate used is FR-4. The design is optimized for 3.5 and 5.8 GHz frequencies, respectively, suitable for WLAN and WiMAX applications. The designed antenna is analysed with perfect boundary on fixed integration technique. There are two-levels of excoriation for the stacked equilateral triangle construction.

R. Ghatak et al. [69] developed a novel and compact CPW fed Sierpinski carpet fractal shaped UWB antenna design with hexagonal boundary having compact size of $33 \text{ mm} \times 32 \text{ mm}$. Proposed antenna has compact size and omnidirectional radiation pattern. The antenna is incorporating a 'Y' shaped slot to reject a band of 5.15-5.825 GHz. The measurement of peak gain varies from 1.25 dBi to 6 dBi. Antenna is suitable for UWB application with distortion-free design. The geometry of proposed antenna is shown in fig. 6 below:

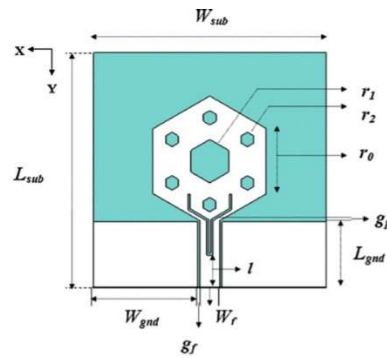


Fig. 6. Sierpinski carpet shaped antenna with hexagonal boundary [69]

Shrivishal Tripathi et al. [70] investigated an ultra-wideband (UWB) monopole antenna based on fractal geometry that resembled Minkowski structure as shown in fig. 7. This antenna design makes use of the fractal geometry's numerous resonance properties to produce the wideband phenomena. The fractal geometry uses the space filling feature to give a wider operational bandwidth and a greater effective antenna length. The use of several slots in the ground plane is intended to enhance the reflection coefficient over the whole UWB frequency range. With an optimal diameter of $23.5 \times 26.5 \text{ mm}^2$, the suggested antenna can operate within the frequency range of 1.4 to 10.4 GHz. The suggested antenna has an almost omnidirectional radiation pattern and correct impedance matching over the whole UWB frequency spectrum.

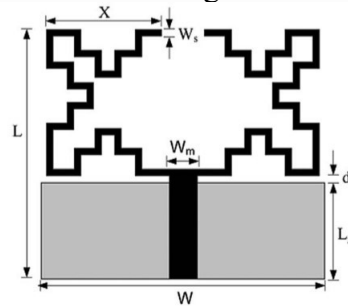


Fig. 7. Ultra-wideband antenna using Minkowski-like fractal geometry [70]

Avinash Kumar et al. [71] studied a reconfigurable microstrip meander line antenna that is suitable for Direct-To-Home (DTH) satellite communication, Wi-Fi devices, and climatic radar systems by using the switching of currents produced by two PIN diodes. The reconfigurability feature of the proposed structure makes it ideal for portable applications due to its compact design. The authors also conducted parametric study of spacing between the meander lines and noted how decreasing the meander line spacing affected the antenna's radiation characteristics, VSWR, and reflection coefficient. The proposed structure is represented in fig. 8 below:

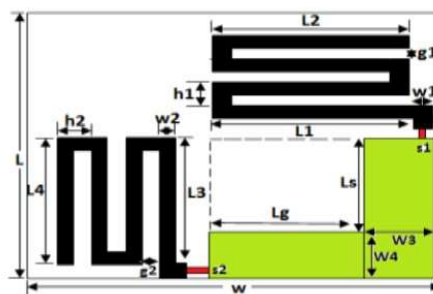


Fig. 8. Reconfigurable Microstrip meander line antenna [71]

Mohd H. Ramli et al. [72] designed a Sierpinski Gasket Fractal Antenna and incorporated slits aiming at compact dimensions, low profile, multiband/broadband. Two methods are used

to achieve desired results are adding slits and increasing iterations of fractal antenna as illustrated in fig. 9. The antenna exhibited a return loss of -11.466 dB and -8.3543 dB at 2.4 GHz and 5 GHz respectively. The proposed antenna design is created in CST software. The design exhibited increased gain when slits are added to SGFA. Introduction of DGS in the design is done to increase bandwidth and miniaturize antenna size.

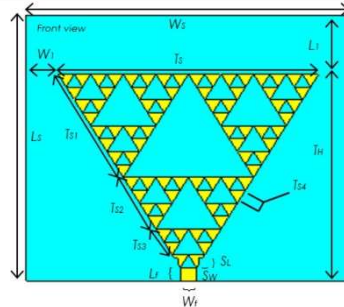


Fig. 9. Sierpinski gasket fractal antenna for multiband applications [72]

S. Singhal et al. [73] discussed the need for super wideband (SWB) antennas in wireless communication systems. Various SWB antenna structures reported in the literature are reviewed by the author. The author devised a compact hexagonal Sierpinski fractal antenna for super wideband applications. The antenna consists of a hexagonal radiation patch with two iterations of Sierpinski square slots as mentioned in fig. 10. Impedance matching is achieved using a CPW feeding. The antenna exhibits an impedance bandwidth of 3.4-37.4 GHz, with a bandwidth ratio of 11:1. The antenna is omnidirectional, reasonably stable, and has good radiation performance characteristics. There is good agreement between the simulated and experimental results. Compared to earlier arrangements, the developed antenna has the benefits of a broader bandwidth and a smaller size.

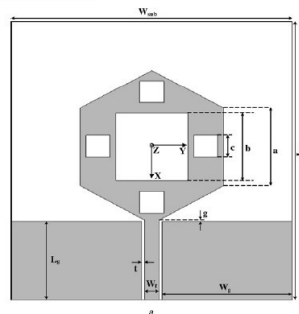


Fig. 10. CPW-fed hexagonal Sierpinski fractal antenna [73]

S. Singhal et al. [74] developed a coplanar waveguide fed octagonal super-wideband fractal antenna integrating defected ground structure. The author utilized the fact that Fractal geometry allows for compact, multiband, and wideband antenna designs and Fractals have convoluted shapes that increase bandwidth and effective radiation. Author also studied several super-wideband antenna configurations. Stable and omnidirectional patterns, among other desirable radiation performance qualities, are achieved. The simulated and experimental results correlate rather well. In comparison to earlier designs, the antenna has a larger bandwidth and a smaller overall size.

Yogesh K. Choukiker et al. [75] devised an antenna for wideband applications by utilizing frequency reconfigurable Koch snowflake characteristics. Frequency reconfigurability is achieved using RF PIN diodes, lumped capacitor, and inductors. The proposed design structure combines the equilateral triangles together with Koch fractal design. A recursive process using the self-similar Koch fractal structure is used to construct the antenna shape. Designed antenna has three operating frequency bands- 3.34 to 4.52 GHz, 2.2 to 3.4 GHz and 1.45 to 4.1 GHz.

The antenna provides continuous wideband frequency coverage and excellent impedance bandwidth from 1.45 to 4.52 GHz. The antenna's performance is verified by measurements, which show that it produced low cross-polarization, steady, and omnidirectional radiation patterns. The compactness of the developed antenna makes it possible to employ it as an array element.

R. Hussan M et al. [76] designed a microstrip fed printed monopole antenna and utilized Cantor fractal geometry on rectangular patch up to second iteration as shown in fig. 11. The substrate used is having relative permittivity of 4.4 and thickness of 1.6 mm. Etching of the monopole radiating element is done on a substrate. Antenna is fed with a 50-ohm microstrip line. The EM simulator and IE3D are used for modelling and performance assessment, and a parametric analysis of the impact of the radiating element's aspect ratio is also carried out. With -10 dB impedance bandwidths in the 1-6 GHz range, dual-band resonant behavior is observed, supporting wireless communication systems like Bluetooth, WLAN, and ITS.

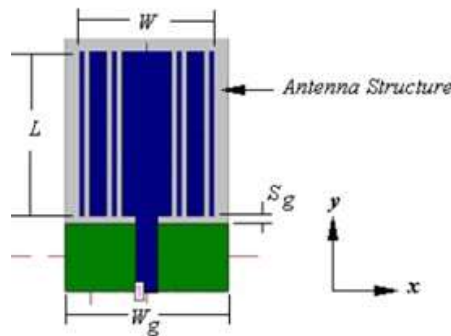


Fig. 11. Cantor based monopole antenna with reduced ground plane [76]

F. Wang et al. [77] proposed and developed a novel Minkowski fractal-based method for bandwidth increase and antenna downsizing. Sensitivity analysis is used to ascertain how important parameters affect the impedance bandwidth. By measuring fidelity factors, radiation patterns, return loss and transfer function, the author conducted an experimental validation of the theoretical study. Asymmetric strips with Minkowski fractal shape increase electrical length while decreasing low cut-off frequency. At higher frequencies, improving the fractal direction enhances impedance matching. Asymmetric strips and Minkowski fractal geometry are used to achieve miniaturization. Impedance bandwidth is increased by a triangle notch.

C. Figueroa-Torres et al. [78] proposed a novel fractal antenna for super wideband applications that is based on the Sierpinski triangle shape and has a modified ground plane as depicted in fig. 12. The antenna has a 15:1 bandwidth ratio and works between 1.68 and 26 GHz. The antenna is 62 by 64 mm in size and has an average gain of 3 dBi. Mobile phones and other portable gadgets can include the innovative design antenna. Performance is enhanced by semi-circular sectors in the radiating patch and small gaps on the ground plane. At higher frequencies, the radiation patterns become directed with side lobes.

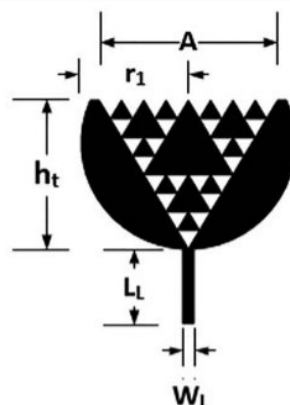


Fig. 12. Fractal antenna based on Sierpinski structure for super wide-band applications [78]

T. Benyetho et al. [79] discussed wireless power transmission using microwave energy. The focus is on increasing the efficiency of energy transmission. The author developed a new multiband antenna integrating microstrip patch technology and fractal antenna geometry. The antenna is validated in simulation and measurement are verified in the ISM band ranging from 2.45 GHz and 5.8 GHz. Its gain is suitable for the mentioned frequency range and its aperture angle is wide. The antenna can be used in a circuit requiring reception of multiple frequencies. The antenna is inexpensive, easy to construct, and appropriate for uses involving wireless power transfer. The design has a small size of $60 \times 30 \text{ mm}^2$ fabricated on FR4 substrate with dimensions of $60 \times 30 \text{ mm}^2$.

A. Reha et al. [80] iterated that antennas with miniaturized design are necessary for restricted environments exhibiting multi-band and broadband characteristics. Miniaturization techniques are studied including geometric manipulation and material manipulation. The author presented a coplanar waveguide fed Sierpinski curve fractal antenna. A lower resonance frequency is made possible by altering the rectangular geometry of the initial iteration of the Sierpinski curve fractal structure. The resonant frequency is further reduced by higher iterations of the fractal structure. Thus, a realistic link between the number of iterations and resonance frequencies is established. CADFEKO is used to acquire the results, and Vector Network Analyzer is used to confirm them through measurement.

Binod K. Soni et al. [81] designed a Minkowskized fractal like antenna using Boolean addition of two shapes i.e. isosceles triangle and a square, forming a non-uniform pentagon shaped patch as shown in fig. 13. He also incorporated a parasitic patch imprinted on deformed ground plane. This hybrid fractal structure exhibited multiple resonant frequencies at 0.83 GHz, 2.12 GHz, 1.05 GHz, 3.75 GHz, 1.6 GHz, 3.25 GHz and 5.2 GHz with sufficient bandwidths suitable for GSM, WiFi, WiMAX, WLAN services. The author exploited the benefit of larger perimeter provided by minkowski shape structure which aids the current vectors to travel around the antenna structure.

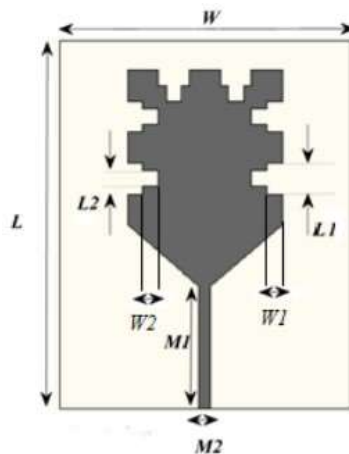


Fig. 13. Minkowskized hybrid fractal antenna [81]

Thilai Thilagam et al. [82] suggested creating slits on the patch surface to create a circular microstrip meander line patch antenna for wireless mobile applications. The author also stacked another hexagonal patch over the meandered circular patch in the final design and achieved the multiband behaviour for frequency range 0.72 GHz to 6 GHz. A gain of maximum value 7.74 dBi is achieved in the proposed structure. The meander technique incorporated in the patch provided increased electrical length and stacking of another patch increased the operational bandwidth of the designed antenna. The antenna design is developed in three stages wherein simple circular patch is designed in first stage. In second stage, circular patch is meandered by

cutting slits on it and finally novelty is introduced in the design by stacking hexagonal patch over the meandered patch.

Mohd G. Siddiqui et al. [83] proposed an A-shaped triangular patch and then used the fractal concept to lengthen the patch's effective length, which produced multiband behavior at frequencies of 11.44 GHz, 13.178 GHz, 15.482 GHz, 19.902 GHz, and 23.529 GHz. This made the patch antenna suitable for use in commercial and X-band, Ku Band, and K Band satellite communication applications. The author exploited the benefits of Von Koch's snowflake concept for employing fractal structure on A shaped patch as shown in Fig. 14.

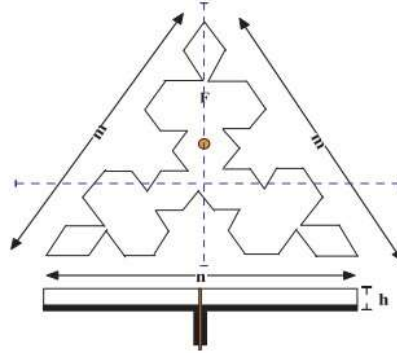


Fig. 14. Multi-Band triangular microstrip fractal antenna [83]

Ashwini Kumar et al. [84] focuses on radio navigation services for ships using multiband antennas. Using an HFSS simulation tool, the Minkowski fractal antenna is parametrized. To accomplish multiband functioning and decreased size, fractal geometry is applied. With a gain of 2.5 dB at 9.4 GHz and 6.3 dB at 3 GHz, the proposed antenna functions at both frequencies. Antenna radiation and resonance characteristics are measured experimentally. Measured outcomes and simulated outcomes accord well. Antenna has nearly Omni-directional radiation patterns in the XZ-plane. To determine the ideal bandwidth in the targeted bands, ground plane width is parametrically optimized. The antenna is tuned to resonant at 9.4 GHz (9.13 GHz to 9.98 GHz) and 3.0 GHz (2.905 GHz to 3.094 GHz), covering frequency ranges for marine radio navigation services with an adequate impedance bandwidth.

Majed O. Dwairi et al. [85] provided a fractal regular slots patch antenna design for use in UWB systems. A UWB monopole rectangular patch antenna serves as the reference antenna. The antenna properties are altered by randomly inserting twenty of the intended fractal slots. Following that, four different antenna topologies are examined with respect to a range of factors, including group delay evaluation, radiation patterns, surface current distribution, gain, and impedance bandwidth characteristics. It is analysed that fractal slots create filtering behavior and band rejection characteristics. A good radiation pattern with a maximum gain of more than 4.97 dBi is observed, shifting from a directive-monopole to a somewhat omnidirectional pattern. The group latency varies by less than 4 nsec, however it is generally consistent. Because the antenna resonantly operates at WLAN IEEE802.11a and HIPERLAN2 systems running in the 5.15-5.825 GHz band and X-band (7.25-7.75 GHz), it is appropriate for UWB applications, satellite applications, and defence systems.

Hiwa Taha Sediq et al. [86] exploited the benefits of employing slots to get multiband behaviour. When slots are added to a microstrip antenna patch, discontinuities are included in the electric current's path, providing additional band frequencies. Fig. 15 shows the proposed geometry. This technique results in multiple operating frequencies exhibited by proposed antenna making it suitable for mobile and wireless devices. In order to increase the overall length of the current path, the suggested antenna consists of a star monopole patch with a slit gap, a star-shaped slot on the patch as the radiating component, and twin square-shaped slots

on the material as the ground plane. It is easy to use the suggested architecture for Ku band, X-band, WLAN, WiMAX, and satellite communications applications.

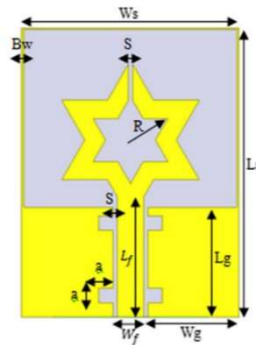


Fig. 15. Multiband monopole fractal antenna for various broadband applications [86]

Fatima Ez-Zaki et al. [87] designed a hexagonal shaped microstrip patch antenna. The designed antenna can be suitably used for vehicular communications including LTE WiMAX and V2XDSRC as it covers navigational frequencies of WiMAX at center frequency of 3.7 GHz and IEEE802.11p at center frequency of 5.9 GHz. Antenna design includes inset feeding mechanism, Cantor fractal slot with partial ground plane. Antenna resonates well in the assigned frequency bands for DSRC/IEEE802.11p and LTE/V2X. The gain of the designed antenna varies from 3.06 to 5.25 dB. The antenna covers multiple wireless communication systems such as blind spot detection, WLAN, WiMAX, and DSRC. Fabricated antenna shows good results, suitable for wireless applications.

A. Annou et al. [88] proposed a novel technique to enhance the gain and radiation efficiency by collaborating defected ground structures with Koch snowflake fractal design on which unit cell of metamaterials is engraved to achieve triple band operation. A multi-resonance L-DGS antenna with a high gain of 5 dB and an efficiency of 99.6% is designed by the author. A new compact double negative metamaterial unit cell and its corresponding circuit are being studied for multi-band (2.8 GHz, 4.1-4.45 GHz, and 5.6 GHz) wireless applications with high miniaturization of 30 x 30 mm². To enhance the antenna matching, a Koch snowflake fractal is inserted along the radiation patch borders. By placing a unique modified CSRR unit cell in the center of a rectangular radiating patch, the antenna size is reduced by 63%. The design is then suitable for WLAN and WiMAX applications because the radiation properties and return loss are enhanced through the use of the DGS and Koch snowflake fractal techniques.

Devesh et al. [89] presented a Miniaturized Hexagonal Sierpinski Gasket antenna for applications focussing on Wireless communication. High gain performance, dual polarization, and multiband operation are attained by the designed antenna. The simulation program HFSS v15 is used to analyse the design. Since fractal antennas with wideband, multi-band, high gain, and improved radiation properties are in demand, Sierpinski gasket fractal structures are employed for multiband operations. With multiband performance demonstrated at 3.46, 8.28, 12.26, 17.21, 23.40, and 26.01 GHz, the design is applicable to 5G and IoT applications, as well as satellite and radar communications. The proposed structure is illustrated in Fig. 16.

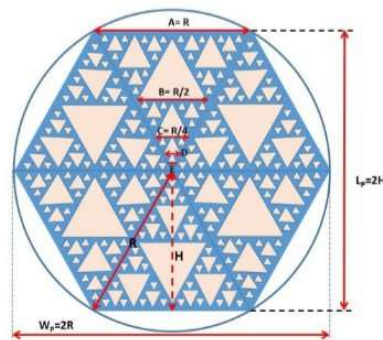


Fig. 16. Hexagonal Sierpinski gasket fractal microstrip antenna [89]

Ashwini Kumar et al. [90] demonstrated, as seen in Fig. 17, a modified Hilbert curve fractal antenna with a dual-layer substrate supplied by a modified coplanar waveguide CPW feed. To increase bandwidth, the scientists used the Dragonfly optimization approach, which is based on swarm intelligence, to improve the shape of the step feed. With a bandwidth of 0.315 GHz (0.68–0.99 GHz), 3.220 GHz (3.98–7.20 GHz), 2.955 GHz (8.043–10.998 GHz), and 1.94 GHz (12.7–14.64 GHz), the antenna offered multiband resonating characteristics. This made it suitable for the Ultra High Frequency (UHF) band as well as the aeronautical radio navigation service (ARNS) in C-band, X-band, and Ku-band. Additionally, the design has parasitic patches that are stimulated via gap coupling. IFS is used to provide geometrical descriptors for the suggested design.

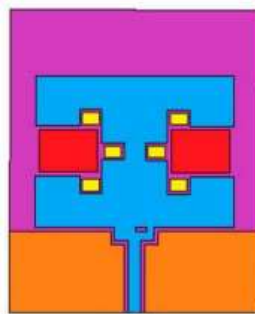


Fig. 17. Hilbert curve fractal antenna [90]

Ashish Kumar et al. [91] investigated the possibility of optimized Sierpinski Fractal Antenna with monolithic microwave integrated circuits for wireless applications in X band and Ku band. Because of the limited space, the author emphasized the necessity of high index substrate materials for MMICs. The limitations of surface waves in high index substrates have been addressed by a novel technique called bulk micro-machining, which produces an air cavity beneath the patch, further creating a low index environment in the patch antenna and leading to a significant improvement in performance parameters as well as compatibility with monolithic microwave integrated circuits, as illustrated in fig. 18. Excellent and highly competitive results are obtained at resonant frequencies of 8.29 GHz, 11.93 GHz, and 15.3 GHz by using the ant lion optimization technique. 9.6 GHz has produced the highest gain of 6 dB, and 8.29 GHz produces outstanding impedance matching of -26 dB.

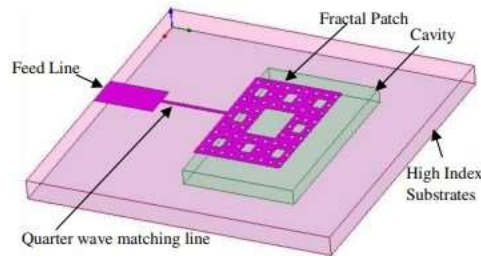


Fig. 18. Micro-machined Sierpinski carpet fractal antenna [91]

Lan Wang et al. [92] suggested an innovative approach of designing multiband antenna using circle and triangle fractals with microstrip line feed represented in fig. 19. With straightforward geometry, the wideband properties are obtained at frequencies 2.6 GHz, 3.8 GHz, 5.3 GHz with adequate gain ranging between 2.58–3.34 dBi. By modifying the antenna radiating slot, the current direction on the microstrip antenna's metal surface is changed to produce multiband coverage. Further the results are enhanced by designing a resonator ring on the ground plane. The antenna model is expandable based on the recommended construction. The antenna may be more fractal outward at lower frequencies and more fractal inward at higher frequencies.

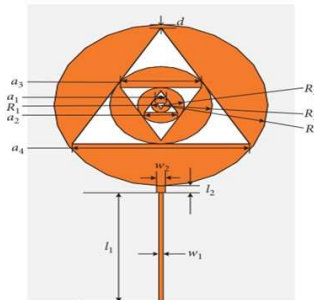


Fig. 19. Multiband antenna using circle and triangle fractals [92]

Nontuthuko L. Nhlengethwa et al. [93] developed a dual band and triple band fractal microstrip patch antenna for WLAN and ISM wireless applications using a basic Sierpinski carpet fractal. In order to obtain multiband behaviour, the author deployed self-similar fractal structures that increases the effective electrical length. As a result, the resonant frequencies of 2.4 GHz, 5.3 GHz and 5.9 GHz are achieved. The suggested antenna is designed to increase its gain and directivity by use of a faulty ground construction that has a reflector plane. The final TBFMPA is showing a maximum directivity of 8.536 dBi at 5.889 GHz and a maximum gain of 2.9 dB at 2.385 GHz. FR-4 substrate is used to create the design, which has overall sizes of $57.9 \times 53.6 \times 1.5 \text{ mm}^3$, as seen in Fig. 20.

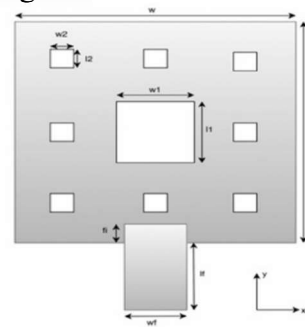


Fig. 20. Sierpinski carpet fractal antenna [93]

Aravindraj Ezhumalai et al. [57] reviewed various fractal structures using IFS. He suggested that a fractal structure may be designed using a variety of methods, but the most popular method for creating a finite set of construction mappings on an entire metric space is Iterated Function System. Among the fractal geometries produced with this method are the Sierpinski carpet and gasket, Koch snowflake, deterministic tree/binary tree, Gosper island, Minkowski island, Cantor set, T-square, and a few space filled fractals. He also looked at fractal structures as a virtual combination of capacitor and inductor that produces a wide range of resonant frequencies in Fractal Patch Antennas. He reaffirmed that IFS offers a crucial foundation for the different fractal structures and their modifications that have been mathematically solved.

Ashwini Kumar et al. [94] suggested a novel antenna design for IoT applications using Minkowski fractal structure. The proposed antenna is miniaturised by 65% using Minkowski fractal. To increase the bandwidth, proposed antenna is fed with microstrip step feed. The sub-6 GHz band is where the multiband behaviour is obtained, spanning a range of frequencies appropriate for 5G communications, public safety applications, GPS, and radar altimeter. After several iterations of inserting slots into the radiating element and partial ground plane, along with parametric optimization, the design is finalized.

Sourabh Raj et al. [95] suggested using the electromagnetic band gap (EBG) structure to create a truncated patch antenna. The fabricated prototype consists of an EBG loaded on the ground plane and a truncated patch with a symmetrical slit. The antenna's optimized volume measures $20 \times 15 \times 1.57$ mm. Over the whole covered bandwidth, a good radiation pattern for the E-H field is established. The antenna covers the bandwidths of 24.2 GHz to 27.84 GHz and 33.84 GHz to 36.2 GHz by resonating at 27.2 GHz and 35.04 GHz. The design may be employed in the Internet of Medical Things and for data transfer from RF sensors to healthcare systems because the antenna spans 5G bandwidth. Furthermore, data transmission and wireless communication are two more uses for antennas in real-time applications.

3. ADVANCES IN HYBRID FRACTAL ANTENNAS

Azaro et al. [96] designed an antenna that operates in GSM and WiFi frequency bands. The design combines a Sierpinski-like structure with a Meander-like structure. Paper focuses on designing miniaturized and multiband antennas for wireless devices. Fractal shapes have been found to be effective for antenna development. Meander-like structure is added for electrical length compliance. The synthesis problem is solved using a PSO algorithm integrated with a method-of-moments simulator. Antenna size is about 50% smaller than a quarter-wave monopole. VSWR value lower than 3.5 required at input port.

Atif Jamil et al. [97] proposed an antenna for WLAN USB dongle with small dimensions and designed a compact Koch-meander Fractal antenna as depicted in Fig. 21. The suggested antenna has high performance attributes together with a large bandwidth. The antenna has the capacity to cover the whole WLAN IEEE 802.11abg standard band. The antenna's bandwidth is 2.2909 - 2.553 GHz and 5.1406 - 5.8737 GHz, with a return loss of -10 dB. At 2.41 GHz, a minimum return loss of -28.9 dB was attained. The suggested antenna could be a good option for the distribution of WLAN USB dongles.

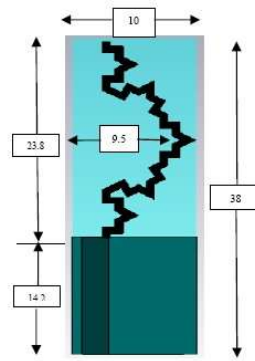


Fig. 21. Hybrid Meander-Koch fractal antenna [97]

Yadwinder Kumar et al. [98] explored the use of Koch and Meander geometry in the creation of a hybrid fractal antenna as depicted in Fig. 22 for wireless applications. The small size and multiband behavior are achieved by the application of fractal geometry. The antenna displays quad band behavior at 4.07 GHz, 7.3 GHz, Bluetooth, and WLAN frequencies because it resonates at four separate frequencies. Its radiation pattern is essentially omnidirectional, its structure is planar, and its cost is modest. The author used MATLAB and the IFS technique to create the hybrid structure.

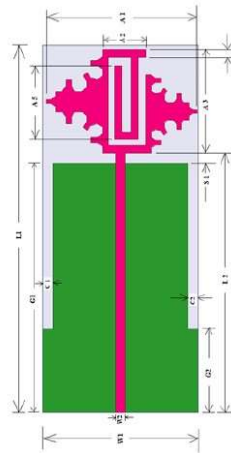


Fig. 22. Quadband hybrid fractal antenna [98]

Amandeep Singh et al. [99] outlined a wideband antenna design based on a modified Sierpinski fractal. The Sierpinski fractal antenna's present layout, mentioned in Fig. 23, is optimized for broadband behavior. Broadband behavior is demonstrated by the developed antenna in the frequency ranges of 21-30GHz and 12.2-13.4GHz. Peak gains that are measured lie between 8 and 22 dB within specific frequency ranges. High gain is obtained by adjusting the original Sierpinski geometry. Results from measurements and experiments with a modified coaxial probe fed antenna are validated. The antenna design is examined and refined by the application of the FEM electromagnetic field solver.

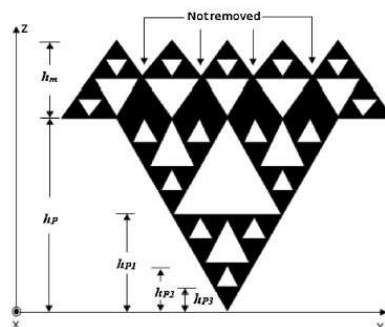


Fig. 23. Coaxial probe-fed Sierpinski fractal wideband and high gain antenna [99]

Yadwinder Kumar et al. [66] devised a unique hybrid fractal antenna design as shown in Fig. 24 utilizing the fractal structures of Koch and Minkowski. The proposed antenna exhibited resonance at seven frequencies covering important frequency bands such as GPS, Bluetooth, WLAN etc as shown in fig. 25 and thus providing applications in mobile/fixed satellite, aeronautical navigation and other wireless applications. The author utilized iterated function system to formulate the hybrid geometry in HFSS. The suggested antenna has acceptable VSWR, gain, and return loss characteristics. This antenna's lightweight and small design make it suitable for usage in portable devices.

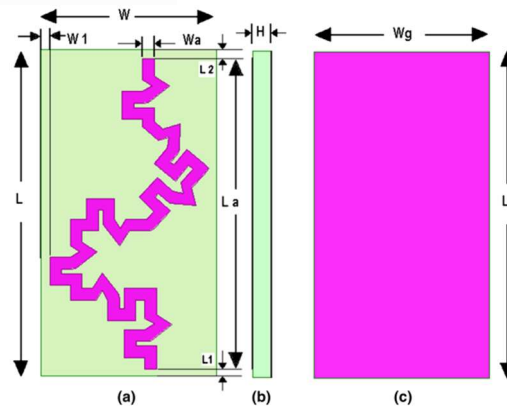


Fig. 24. (a) Top View (b) Side View (c) Back view of Proposed antenna [66]

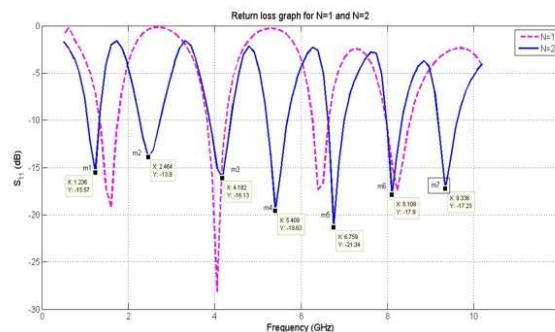


Fig. 25. Return loss of compact multiband hybrid fractal antenna showing hepta-band behaviour

Shrivishal Tripathi et al. [100] created a small UWB antenna with better radiation characteristics and wideband utilizing Sierpinski fractal geometry. Fractal geometry's space-filling characteristics and self-similarity allow for both miniaturization and wideband features. The effective electrical channel length can be increased by combining the Sierpinski fractal with octagonal-shaped geometry. The antenna has a good return loss and almost omnidirectional radiation pattern. The measured features of the designed prototype match simulation, and it exhibits an excellent time domain response with compact dimensions of $25 \times 16 \text{ mm}^2$. An analysis of surface current distribution is conducted to comprehend the radiation process.

Yadwinder Kumar et al. [101] proposed combining a Meander-like antenna (for lower frequency) with a modified Sierpinski gasket to create a hybrid fractal structure. With resonant frequencies of 2.4 GHz, 4.437 GHz, 5.38 GHz, 7.01 GHz, 7.60 GHz, 8.41 GHz, and 9.09 GHz, the suggested radiating structure displays multiband behavior. This makes the developed antenna appropriate for radiolocation, Bluetooth, WLAN, Wi-Fi, ISM, RFID, 4G/LTE, and mobile/fixed satellite services. In order to achieve an effective value of gain at resonating frequencies, as shown in fig. 26, the author modified the original Sierpinski gasket structure by

varying various parameters like scale factor and flare angle using the IFS mathematical tool. The modified Sierpinski gasket was subsequently paired with a meander-like antenna and a defected ground structure.

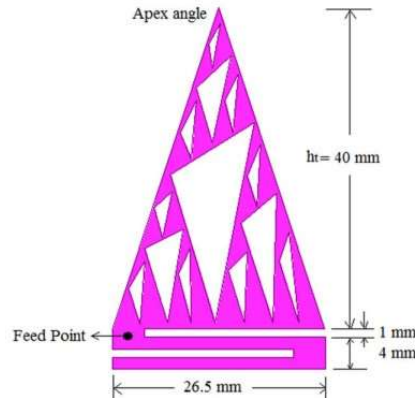


Fig. 26. Sierpinski–Meander hybrid fractal multiband antenna [101]

Manisha Gupta et al. [102] designed a miniaturized and circularly polarized Microstrip fractal antenna using a hexagonal shaped patch for microwave applications in S and X band. The proposed antenna combines the fractal structures of Koch and Sierpinski, with the Koch fractal structure on the edges using a right-angled isosceles triangular construction (Fig. 27). The author studied the importance of circular polarization and concluded with hexagonal shaped patch because it is the closest match of circular patch together with defected ground structure to accomplish circular polarization. The proposed structure exhibits multiband behaviour at resonant frequencies 3.1 GHz, 6.9 GHz, 8.4 GHz and 9.1 GHz together with sufficient gain with circular polarized radiation patterns making it suitable for mobile TV, satellite radio, home-based consumer electronics, radars, satellites and military applications.

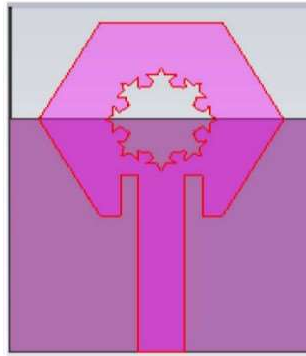


Fig. 27. Koch fractal-based hexagonal patch antenna [102]

Devesh et al. [103] integrated both Sierpinski Gasket and Sierpinski Carpet to utilize the benefits of fractal antenna which help in achieving miniaturisation of the overall dimensions of antenna as clear from Fig. 28. The author also discussed other methods of achieving multiband operations like usage of thick dielectric substrate, slots and notches included in the patch etc and concluded that these techniques lead to larger and bulkier design of antenna. The designer is able to achieve multiband as well as wideband response by creating four triangular slots in square patch structure and repeating the same structure up to four iterations. The resonating frequencies 15.92 GHz, 20.05 GHz, 23.08 GHz and 27.77 GHz as shown in fig. 29 are suitable for K Band and Ku Band wireless applications like satellite communication and radar communication.

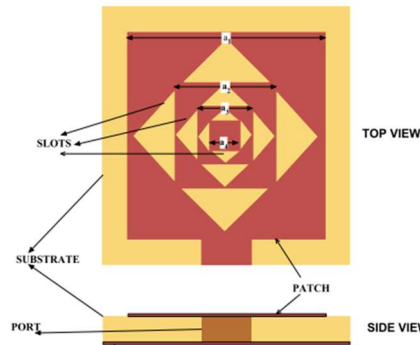


Fig. 28. Modified square Sierpinski gasket fractal microstrip antenna [103]

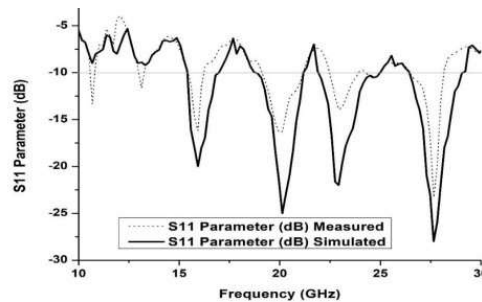


Fig. 29. Return loss of modified square Sierpinski gasket fractal microstrip antenna depicting quadband response

Manisha Gupta et al. (2018) [104] designed, fabricated, and measured a hexagonal fractal patch antenna that is inset fed. The antenna has a hexagonal form with edges that include a Koch snowflake fractal structure. The frequency range for ultra-wideband characteristics is 3.265 GHz to 8.2 GHz. The antenna is appropriate for multiband and circularly polarized radiations in wireless systems as observed and simulated results correspond well. The design displays radiation patterns that are bidirectional in the E-plane and omnidirectional in the H-plane. Applications for the prototype antenna include weather radar systems, Wi-Fi devices, cordless phones, and satellite communication.

Roman Kubacki et al. [105] introduced an ultra-wideband antenna that uses fractal architecture based on planar repetition. Through an increase in electrical length and resonant bands, fractal geometry enhanced the antenna's broadband properties and gain. The design of the double-fractal layer antenna allowed a frequency range of 4.1 to 19.4 GHz, with a bandwidth of 15.3 GHz. The highest gain of the designed antenna is 10.9 dBi at 15.2 GHz, with an average observed gain of 6 dBi. The outcomes demonstrated that efficiency increased as frequency increased. The suggested antenna can be applied to communication systems that call for more advanced characteristics.

Ashish Kumar et al. [106] concentrates on adapting the Pythagorean fractal tree patch antenna for multiband usage. The antenna is made on a FR4 substrate that has a thickness of 0.8 mm and a dielectric constant of 4.4. With a maximum gain of 4dBi, the final design iteration exhibits multiband characteristics with frequencies spanning from 1.38 GHz to 18.09 GHz. Patch antenna bandwidth is improved by thickening the substrate. High index materials and a micromachining technique are used in the integration of patch antenna with MMICs to design the patch on the high index material. Patch antenna bandwidth issues are solved by using a composite substrate or micromachining, which makes the design appropriate for satellite services related to earth exploration.

Norun Abdul Malek et. al [107] suggested the creation of a hybrid Koch-Minkowski Fractal Dipole antenna for use in dual band wireless applications. Particularly at the low frequency of 900 MHz, which is designated for IoT communication for sensors, attenuators, transceivers,

and processors, hybridization led to the shrinking of antenna for IoT applications. The goal of the research is to determine how much antenna size may be decreased while still allowing the fractal to resonate at the desired frequency. In this work, the fractal antennas demonstrated dual frequency operation at 900 MHz and 2.6 GHz, with return losses of 18 dB and 16 dB, respectively. The antenna's compact, lightweight, and thin form (115 x 22.5 x 0.285 mm) makes it a desirable feature for compact wireless applications.

Mohd Gulman Siddiqui et al. [108] proposed a fractal antenna for C/X/Ku-band applications by utilizing dual fractal approaches based on Koch and Sierpinski fractals. To lessen the impact of surface currents, the Koch fractal idea is applied to the square-shaped patch's outside perimeter and the Sierpinski gasket concept is used to its interior segment. Three substrates—Fr4, Rogers RO 4003, and Rogers Ultralam—have design outcomes that are compared, with a size reduction around 57.2% obtained. With return losses of -38.906 dB, -23.58 dB, -26.19 dB, -34.06 dB, and -30.01 dB, respectively, the antenna resonates at 5.699 GHz, 10.108 GHz, 11.100 GHz, 15.812 GHz, and 17.621 GHz, demonstrating its suitability for commercial wireless and satellite applications.

Atif Jamil et al. [109] proposed a novel fractal antenna keeping in view the miniaturisation and wideband operation requirements of sophisticated wireless devices. The designed antenna merges meander and Koch curve shapes as shown in Fig. 30 and it is compared with standard Koch curve geometry also. The designer exploited the benefits of combining non-fractal meander line with fractal Koch curve using IFS to bring the higher modes together and achieved wider bandwidth. The parametric optimization is also done in CST MWS to achieve adjusted thickness of the ring of value of 1.1 mm and width of ground plane of 25 mm. By lengthening the antenna's total electrical length and, consequently, the number of segments that make up the resulting convoluted form, miniaturization is accomplished.

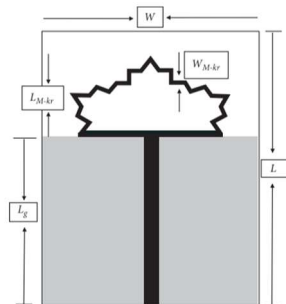


Fig. 30. Wideband hybrid fractal antenna [109]

Omaima Benkhadda et al. [110] developed a Sierpinski Hexagonal shaped radiating element and incorporated partial ground plane loaded with three rectangular stubs and three rectangular slits. The proposed structure is shown in fig. 31 and it resonates in three frequency ranges of 2.19–4.43 GHz, 4.8–7.76 GHz, and 8.04–11.32 GHz, thus named as tri-wideband fractal antenna suitable for use in variety of wireless technologies such as LTE 2300, LTE 2500, RFID, Bluetooth, 5G spectrum band, WLAN, Industrial, Scientific and Medical (ISM), Worldwide Interoperability for Microwave Access WiMAX, C-band, and X-band.

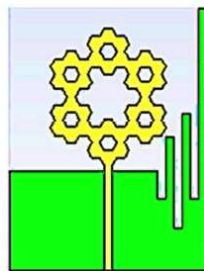


Fig. 31. Sierpinski hexagonal shaped antenna [110]

Rakhee Patil et al. [111] presented the design and optimization of a Sierpinski Carpet fractal antenna using Artificial Neural Network appropriate for operation between 2 GHz to 8 GHz. The structure is shown in fig. 32. The antenna is simulated using HFSS and microstrip line feeding technique is utilized to feed the proposed antenna. In this implementation, the neural network predicts significant parameters, such as s_{11} and VSWR values, based on frequency. A Multilayer Feed Forward Artificial Neural Network is used in the suggested method as an approximation model to determine different antenna parameters.

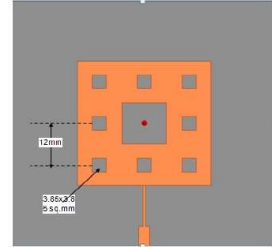


Fig. 32. Sierpinski carpet fractal antenna [111]

N.M. Mary Sindhuja et al. [112] introduced a novel slotted fractal antenna design with inset fed incorporating $\beta\Omega$ space filling curve as shown in fig. 33 capable to resonate at multiple frequency bands. The antenna resonating at 1.91 GHz, 3.12 GHz, 5.56 GHz, 10.75 GHz and 13.94 GHz is suitable for various applications such as PCS-1900, rail mobile radio, DCS-IMT gap, WCDMA, X-band and Ku band services. The parametric study by varying the ground plane length is done and optimized performance of antenna is achieved at ground plane length reduced to 50 %.

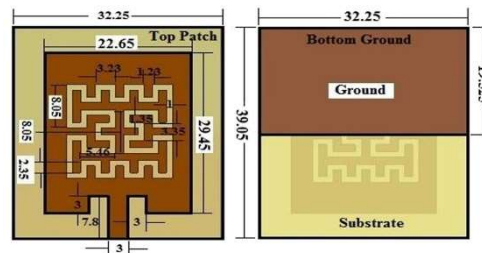


Fig. 33. Hybrid $\beta\Omega$ -indexing based fractal antenna [112]

Rania Hamdy Elabd et al. [113] presented a circular ring-shaped fractal antenna incorporating a central plus sign and an outer circular ring with eight smaller rings to enhance the bandwidth for UWB response. The proposed design is demonstrated in fig. 34 below. The author optimized the dimensions of antenna using Particle Swarm optimization techniques while maintaining the satisfactory return loss response. The antenna covered diverse wireless standards like UWB from 3.1 up to 10.6 GHz, X-band from 8 up to 12.5 GHz, and lower band of Ku from 12.5 to 14.5 GHz. The fractal antenna's bandwidth is increased by mitigating extra capacitive reactance by plus sign which also couples with the partial ground plane.

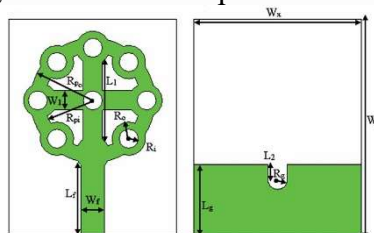


Fig. 34. Circular ring-shaped UWB fractal antenna [113]

Sanae Attiou et al. [114] presented a novel ultra-wideband (UWB) fractal antenna design that integrates Sierpinski carpet and Giuseppe Peano geometries along with a uniquely

structured ground plane to enhance bandwidth performance. Utilizing HFSS for simulation, the proposed compact antenna demonstrates effective operation across a broad frequency spectrum of 3.32 to 11.96 GHz, achieving a peak gain of 5.6 dB. Designed for a variety of wireless applications—including sub-6 GHz 5G, WiMAX, WLAN, C-Band, and X-Band satellite communications—the antenna's performance was further validated through fabrication on an economical FR4 substrate. The measured results closely align with simulations, confirming the antenna's wide impedance bandwidth and strong radiation characteristics. Its compact form factor and broad usability make it a promising solution for modern UWB communication systems.

Prasannajeet Mohanty et al. [115] introduced a hybrid fractal microstrip antenna design which merged Vicsekcross and Koch fractal geometries to exploit the strengths of both designs. The Vicsekcross structure contributes to antenna miniaturization through its space-filling nature, while the Koch curve enhances gain and bandwidth via its self-similar configuration. The VKFA demonstrates a compact, low-cost design fabricated on an FR4 Epoxy substrate, operating effectively across 16.92–18.74 GHz with a peak gain of 5.14 dBi at 17.19 GHz. Notably, circular polarization is achieved using two L-shaped slots etched 180° apart on the patch, producing orthogonal modes with a 90° phase shift, resulting in right-hand circular polarization and a 3-dB axial ratio bandwidth from 17.12 GHz to 18.04 GHz.

4. COMPARATIVE ANALYSIS OF HYBRID FRACTAL ANTENNAS

The comparative analysis of various UWB fractal antennas is discussed in this section. The parameters like resonant frequency, gain, operating band, bandwidth and dimension of the fractal antennas are compared and listed in Table 1.

Table 1. Comparative analysis of hybrid fractal antennas

Ref. No.	Design	Dimensions	Substrate Type	Multiband Response	Gain	Applications
[96]	Sierpinski-like and Meander-like structures	40mm × 40mm × 0.8mm	Arlon $\epsilon_r = 3.38$	Tri-band	--	GSM and WiFi
[97]	Meander-Koch fractal antenna	38mm × 10mm	FR4 $\epsilon_r = 4.34$	Dual-band	2.281 dBi 2.30 dBi	WLAN USB dongle
[98]	Koch and meander geometry	55mm × 24mm × 1.6mm	FR4 $\epsilon_r = 4.4$	Quad-band	4.3 dBi	Bluetooth and WLAN
[99]	Modified Sierpinski fractal antenna	39mm × 40mm × 1.524mm	Rogers RO4003C $\epsilon_r = 3.55$	Dual-band	21.26 dB 8 dB	Broadband satellite receivers, mobile space research activity
[66]	Hybrid Koch Minkowski fractal antenna	28mm × 15mm × 1.58mm	FR4 $\epsilon_r = 4.4$	Hepta-band	4 dB	GPS, Bluetooth, WLAN
[100]	Sierpinski fractal geometry	25mm × 16mm × 1.6mm	FR4 $\epsilon_r = 4.4$	Tri-band	--	Wireless personal area network and wireless body area network
[101]	Modified Sierpinski–Meander hybrid fractal antenna	54mm × 46mm × 1.6mm	FR4 $\epsilon_r = 4.4$	Hepta-band	Max. 32 dB Min. 6 dB	Bluetooth, WLAN, Wi-Fi, ISM, RFID, 4G/LTE
[102]	Koch fractal-based hexagonal patch antenna	30mm × 35mm × 1.59mm	FR4 $\epsilon_r = 4.4$	Penta-band	4.08 dB 4.79 dB 3.85 dB 3.46 dB 3.01 dB	Microwave applications, mobile TV and satellite radio

[103]	Modified Square Sierpinski Gasket (MSSG) fractal antenna	40mm × 40mm × 1.6mm	FR4 $\epsilon_r = 4.4$	Quad-band	6.81 dB 7.91 dB 7.32 dB 8.89 dB	Wireless multi-band communication systems.
[104]	Hexagonal shape with Koch snowflake fractal	32mm × 32mm × 1mm	FR4 $\epsilon_r = 4.4$	Tri-band	6.8dB	Satellite communication transmissions, some Wi-Fi devices, cordless telephones, and weather radar systems
[105]	Minkowski Island and Crossbar Fractal Microstrip Antennas	27.6mm × 31.8mm × 0.79mm	RT/Duroid $\epsilon_r = 2.2$	Tri-band	6 dBi	Communication system
[106]	Modified Pythagorean fractal tree patch antenna	40mm × 37mm × 0.8mm	FR4 $\epsilon_r = 4.4$	Hexa-band	4 dBi	Earth exploration satellite services
[107]	Hybrid Koch-Minkowski Fractal Dipole Antenna	115mm × 22.5mm × 0.285mm	RT/Duroid $\epsilon_r = 2.2$	Dual-band	2.069 dB	Compact Wireless applications
[108]	Koch-Sierpinski Fractal Microstrip antenna	60mm × 50mm × 1.6mm	FR4 $\epsilon_r = 4.4$	Penta-band	--	C/X/Ku-band applications
[109]	Hybrid meander-Koch Fractal ring antenna	45mm × 25mm × 1.6mm	FR4 $\epsilon_r = 4.34$	Wideband	3 dBi	5 GHz WLAN Band
[110]	Sierpinski Hexagonal-Shaped Fractal Antenna	24mm × 30mm × 1.6mm	FR4 $\epsilon_r = 4.4$	Tri-band	1.71 dBi 4.61 dBi 4.46 dBi	WLAN, WiMAX, ISM, LTE, RFID, Bluetooth
[111]	Sierpinski carpet fractal antenna	35.4mm × 35.4mm × 1.58mm	FR4 $\epsilon_r = 4.4$	Hexa-band	--	Wi-Fi & WiMAX
[112]	Hybrid β Ω -indexing based fractal antenna	39.05mm × 32.25mm × 1.6mm	FR4 $\epsilon_r = 4.4$	Penta-band	0.5 dBi, 4.32 dBi 14.9 dBi 22.49 dBi 4.51 dBi	PCS-1900, rail mobile radio, DCS-IMT gap, WCDMA, X-band, and Ku-band services
[113]	Circular Ring-Shaped UWB Fractal Antenna	38mm × 45mm × 1.75mm	RogerRT 5880 $\epsilon_r = 2.2$	Penta-band	6 dBi	UWB applications

CONCLUSION

The development and application of fractal antennas and hybrid fractal antennas represent significant strides in advancing multiband wireless communication systems. Through this review, we have explored the evolution of these antennas and their contributions to overcoming the challenges inherent in contemporary wireless communication. The emergence of hybrid fractal antennas, which combine fractal principles with other antenna technologies, has further expanded the capabilities of multiband communication. By leveraging the strengths of different antenna designs, hybrid fractal antennas achieve enhanced performance metrics, including increased bandwidth, improved radiation characteristics, and greater adaptability to evolving communication standards. In the realm of multiband wireless communication, fractal and hybrid fractal antennas have demonstrated their efficacy across various applications, from cellular networks to satellite communication and beyond. Their ability to operate across multiple frequency bands facilitates seamless connectivity, robust signal transmission, and

efficient spectrum utilization, thereby supporting the proliferation of advanced wireless services and technologies.

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