Progress In Electromagnetics Research Letters, Vol. 94, 109–115, 2020

Saw-Tooth Shaped Sequentially Rotated Fractal Boundary Square Microstrip Patch Antenna for Wireless Application

Mandar P. Joshi[1, *], Vitthal J. Gond[2], and Jayant J. Chopade[1]

Abstract—This paper presents a new saw-tooth shaped sequentially rotated fractal boundary (SRFB) square microstrip patch antenna (SMPA) for wireless application. The square shape is rotated by an angle 'θ' and superimposed, realizing fractal like geometry at boundary. The rotation of square shaped patch is divided in equal number of scaling angles θ_n such that for every iteration of angle θ, fractal boundary geometry has been realized. The square shape is modified into a circular shape patch resonating at 2.5 GHz. A 45° tilted rectangular slot is cut inside the radiating element to achieve circular polarization at 2.45 GHz. The antenna is fabricated using an RT Duroid 5880 substrate, having size of 70 mm×70 mm. The antenna offers measured impedance bandwidth (VSWR $<$ 2) of 50 MHz (2%) with simulated peak gain about 7 dBi. The fabricated antenna is tested, and measured results are in close agreement with simulated ones.

1. INTRODUCTION

The demand of microstrip patch antennas (MPAs) in wireless communication is increasing because of their numerous advantages like low profile, direct connectivity to Radio Frequency (RF) circuitry, planar structure, etc. These MPAs are desirable to offer several characteristics as multiband or broadband response with compact size. Fractals are self-similar structures commonly inspired from nature. Fractal antenna research is primarily focused on developing multiband or compact MPAs [1, 2]. Fractal shaped antenna geometry realizes different performance modifications in MPAs. These self-similar structures can be inside the radiating patch or at an outer edge of patch exhibiting advantages like multiband response or lowering the resonance frequency bands respectively [3–14]. Various fractal shaped antenna geometries such as Sierpinski fractal, Koch fractal, and crown shaped fractals have been designed and developed by different researchers for various wireless applications.

Circularly polarized (CP) MPAs are preferred for wireless communications, as these antennas are unaffected by multi-path propagation delays, Faraday's rotation effects, and direction of transmitter and receiver antennas [15]. These advantages of CP lead to the design of single coaxial feed microstrip patch antennas with circular polarization. The hybrid antenna structure consisting of Koch fractal geometry along with meandered slit and defected ground structure has been reported for wearable wireless body area network application [3]. A wide band circularly polarized tilted fractal slot monopole antenna has been presented in [4]. A compact fractal square shaped MPA for dual-band wireless applications has been reported [5], and a Sierpinski gasket fractal antenna structure and their properties have been discussed in [6].

In last few years, the design and optimization of fractal like geometrical structures and their performance evaluation using many bio-inspired soft computing techniques have been reported. The use of bio-inspired optimization technique along with Artificial Neural Network (ANN) helps to design

Received 20 September 2020, Accepted 29 October 2020, Scheduled 9 November 2020

* Corresponding author: Mandar P. Joshi (mandarjoshi11@gmail.com).
[1] Department of E & TC, Matoshri College of Engineering and Research Center, Nashik (MS) 422105, India. [2] Department of E & TC, MET's Institute of Engineering, Nashik (MS) 422207, India.

compact and broadband MPAs. In [7], a compact crown shaped fractal microstrip antenna optimized by PSO-ANN soft computing technique has been reported. Various fractal structures like hybrid Koch fractal for wideband response [8], CP square shaped Koch fractal for UHF RFID application [9], a CP printed fractal slot geometry antenna for broad impedance and axial ratio bandwidth are presented [10]. All the reported fractal antenna structures are optimized for wideband or multiband response. However, fractal geometries are also reported to realize compact MPAs.

By modifying the edge of MPAs, a boundary fractal structure can be achieved. Using asymmetric slits cut on edge and on center rotated slot of a square microstrip antenna, a tri-band MPA has been realized [11]. A CP MPA has been reported using high impedance surface for wide band applications [12]. A compact CP MPA is presented using asymmetric fractal boundary [13], and a diamond shaped fractal MPA has been presented for multiband wireless applications [14]. An octagon shaped circularly polarized microstrip antenna with a conical radiation pattern is presented [17]. All these reported antenna geometries use complex fractal geometrical structures which need fabrication accuracy.

In this research work, the authors have proposed a new fractal geometry using the concept of rotating square patch at desired angular rotation to get the desired resonance frequency. Sequential rotation and superimposition of similar length square patch shape approach are used to design a fractal boundary microstrip patch antenna. The proposed saw-tooth shaped SRFB square MPA resonates at 2.50 GHz frequency with 76 MHz of simulated impedance bandwidth. A rectangular slot tilted by 45° is etched into the patch to realize the CP response having 20 MHz (2.44–2.46 GHz) of simulated axial ratio bandwidth with maximum gain of 7 dBi, which covers wireless applications like Wi-Fi and Industrial Scientific and Medical (ISM) bands.

2. ANTENNA DESIGN AND GEOMETRICAL EVOLUTION

Figure 1 depicts the proposed fractal boundary antenna geometry and geometrical evolution process. At first, length (L) of the square shaped microstrip patch antenna is calculated using Equation (1) [15]

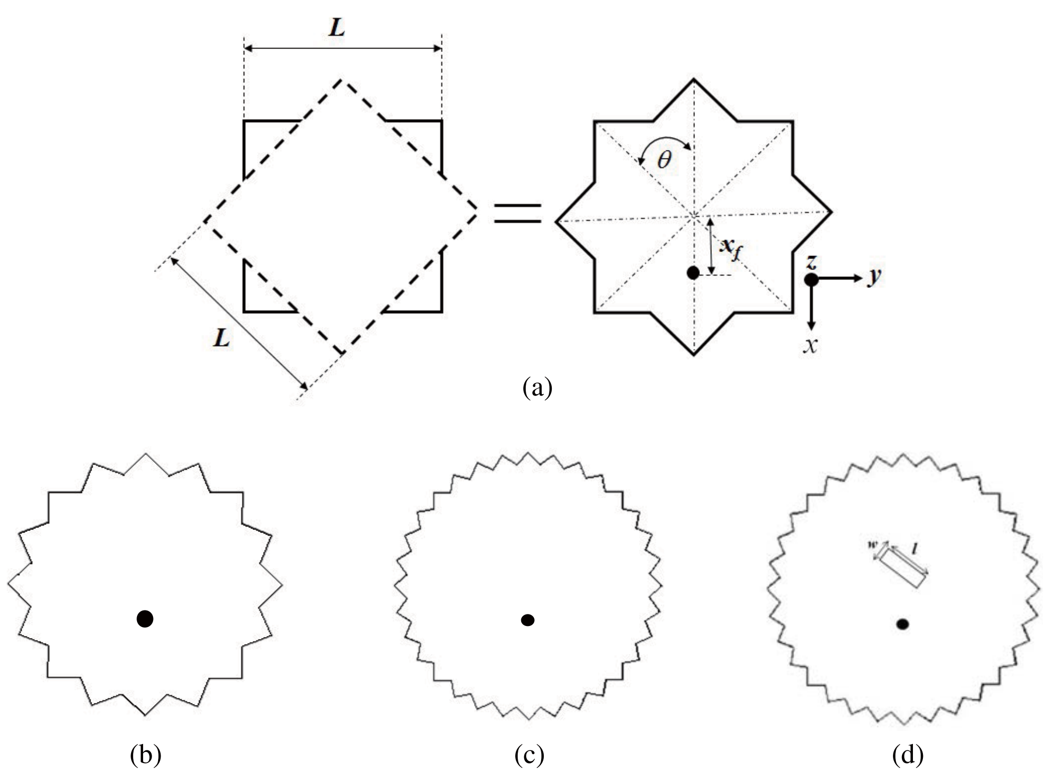


Figure 1. Antenna structure and geometrical evolution (a) 45° rotated square MPA (0th and 1st iteration), (b) SRFB MPA (2nd iteration), (c) SRFB MPA (3rd iteration), (d) Slotted SRFB with CP.

for resonant frequency of 3 GHz. The calculated length using Equation (1) is $L = 33$ mm.

$$L = 0.49 \frac{\lambda_0}{\sqrt{\varepsilon_r}} \tag{1}$$

In Equation (1), λ_0 is the free space wavelength, and ε_r is the relative permittivity of substrate used. In the proposed research work, a Roger's RT Duroid 5880 substrate having thickness $h = 1.57$ mm and $\varepsilon_r = 2.2$ is used to fabricate designed antenna. The feed point is located at $x_f = 5$ mm. An SMA connector with the inner conducting wire diameter of 1.2 mm is used to feed this antenna. This is 0th iteration of proposed fractal boundary shaped geometry. Along with a square shaped patch, another similar length square shape is taken which is rotated by an angle $\theta = 45°$ and superimposed on the previous square shaped patch as depicted in Fig. 1(a) for the 1st iteration. This proposed saw-tooth star shaped 45° rotated superimposed MPA resonates at 2.74 GHz having 50 MHz of impedance bandwidth. The resonant frequency shifts to lower frequency, as equivalent area of patch is increased. Further, the angle $\theta = 45°$ is divided by two $(\theta/2)$ to realize symmetry in antenna structure. This symmetry results into three different angles $\theta_1 = 22.5°$, $\theta_2 = 45°$, and $\theta_3 = 67.5°$, respectively, to achieve the 2nd iteration as presented in Fig. 1(b). To realize the 3rd iteration, $\theta_1 = 22.5°$ is further divided by two $(\theta_1/2)$ to get equal number of angles. The square shaped patch of length $L = 33$ mm is rotated sequentially in the range of angles from θ_1 to θ_7 and superimposed on each other to realize fractal boundary shaped geometry as given in Fig. 1(c). These values of angles are presented in Table 1.

Table 1. Angle of sequential rotation.

Angle	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7
Value	11.25°	22.5°	33.75°	45°	56.25°	67.5°	78.75°

Figure 1(d) presents a 45° rotated rectangular slot of length and width of 8 mm×1 mm which is cut inside the radiating patch to realize CP. This antenna is simulated using Altair's Hyperworks CAD FEKO antenna simulator [16]. An infinite ground plane is used while the antenna structure is simulated. For the fabrication of proposed structure, the size of substrate is taken as 70 mm×70 mm.

The proposed fractal boundary geometry is designed for scaling angle $\theta_s = 45°$. Therefore, the fractal dimensions of this geometry can be calculated using Equation (2) [18].

$$D = -\frac{\log n}{\log\left(\frac{1}{\theta_S}\right)} \tag{2}$$

where θ_s = scaling angle in degree (45°), and n = the number of copies (7). The evaluated value of fractal dimension is $D = 0.5112$. This kind of fractal boundary structure can be applicable to those values of 'θ' having perfect divisibility with 360°. The angle θ_n can be represented and evaluated using Equation (3).

$$\theta_n = \theta_{n-1} + d \tag{3}$$

where $d = {}^{\theta_s}/_4$.

3. SIMULATION RESULTS AND DISCUSSION

In this paper, the concept of sequential rotation of a square patch to realize saw-tooth shaped fractal boundary at an outer edge of MPA is used. The fractal boundary shape converts square shape to equivalent circular like shape resulting in enhancing the overall shape of microstrip patch area. This in turn lowers the resonance frequency from 2.96 GHz to 2.50 GHz. Further, reduction in resonance frequency has been realized by cutting a slot inside the radiating patch. The process of iterations and resonant frequency are depicted and explained using Fig. 2.

As presented in Fig. 2, the square shaped MPA is designed to resonate at 3 GHz. The simulated results show the frequency of 2.96 GHz for the 0th iteration. For the 1st iteration of $\theta = 45°$, the

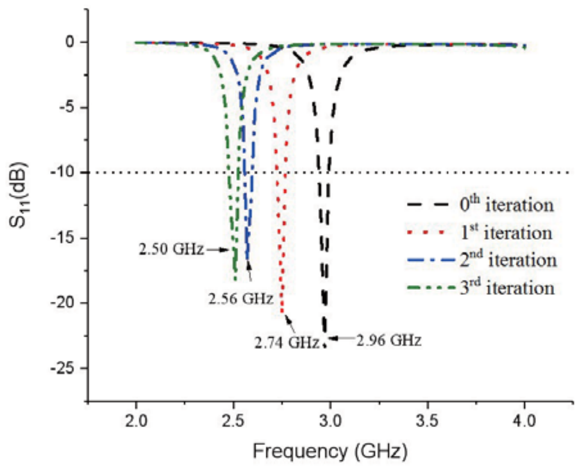


Figure 2. Return loss characteristics SRFB Square MPA.

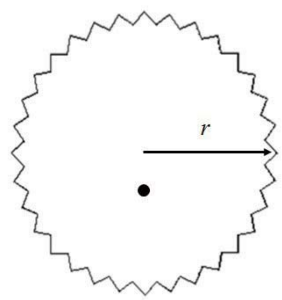


Figure 3. SRFB geometry approximation as circular patch.

resonance frequency shifts towards lower side at 2.74 GHz. For the 2nd and 3rd iterations, the overall area of patch is enhanced, and resonance frequency shifts to lower side with the antenna resonating at 2.56 GHz and 2.50 GHz, respectively. As the angle $\theta = 45°$ is self-divided into equal number of angles to realize symmetry in the structure, the resonant frequency shifts towards lower side. The simulated impedance bandwidth observed at the 3rd iteration is about 50 MHz. The resulting fractal geometry forms an approximate saw-tooth shape of a circular patch having radius of $r = 23.33$ mm as presented in Fig. 3. Using Equation (4), of circular patch antenna, the calculated values of theoretical resonance frequency is 2.54 GHz, which is close to the simulated frequency of the 3rd iteration, 2.50 GHz.

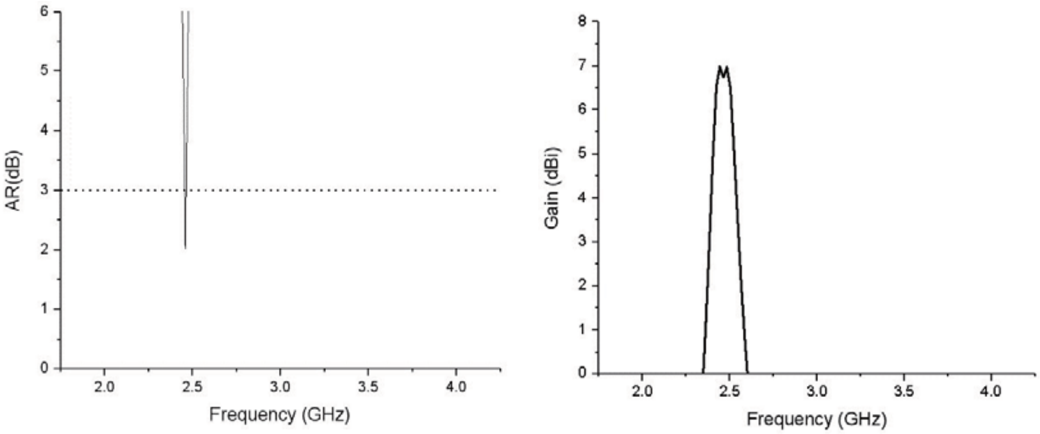
Further, by cutting a diagonal slot inside the patch CP resonance frequency is shifted to lower side, and the antenna resonates at 2.45 GHz with simulated impedance bandwidth of 76 MHz. The simulated axial ratio bandwidth obtained is about 20 MHz covering 2.44–2.46 GHz Wi-Fi and ISM wireless band, having the maximum gain of 7 dBi as depicted in Figs. 4(a) and 4(b), respectively. The parametric analysis has been carried out to decide the dimensions of the rectangular slot.

$$f_r = \frac{1.84118c}{2\pi r\sqrt{\varepsilon_r}} \tag{4}$$

Figures 5(a)–(b) present radiation characteristics of the SRFB square MPA. The radiation pattern is in broadside direction with left hand circular polarization (LHCP) in both E- and H-planes. The slot is rotated by 45° in counter-clockwise directions, and hence the antenna exhibits LHCP characteristics in both planes.

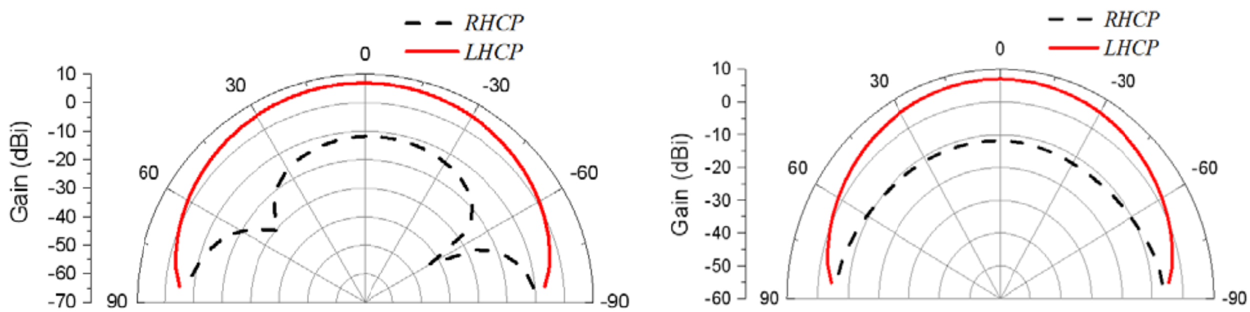
This LHCP characteristics can also be verified by studying surface current distribution as presented in Fig. 6.

As depicted in Fig. 6, the surface current rotates in clockwise direction, and hence this antenna exhibits LHCP. However, if the rotation of rectangular slot is in clockwise direction, then the antenna exhibits right hand circular polarization (RHCP).



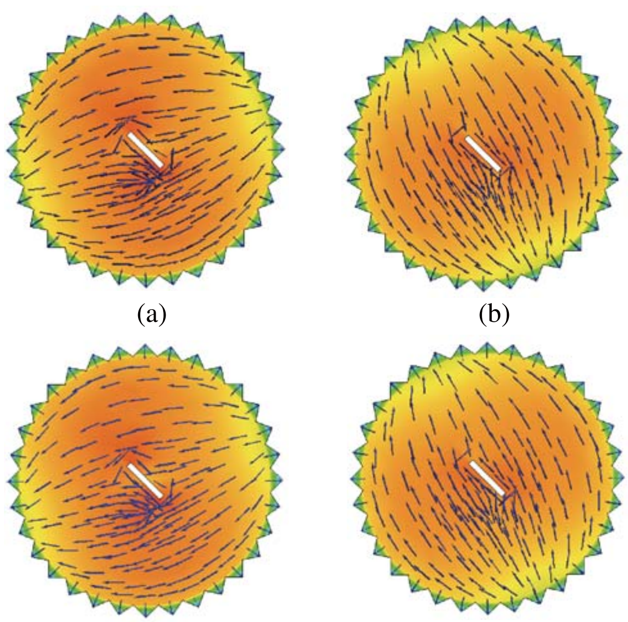
(a) (b)

Figure 4. (a) Simulated axial ratio, (b) simulated gain characteristics.



(a) (b)

Figure 5. Radiation pattern at 2.45 GHz (a) E-plane (b) H-plane.



(a) (b)

(c) (d)

Figure 6. Surface current at 2.45 GHz. (a) 0°, (b) 90°, (c) 180° and (d) 270°.

4. MEASURED RESULTS

The designed and simulated antenna structure is fabricated using an RT Duroid 5880 substrate having dimensions of 70 mm×70 mm. The fabricated prototype is tested using Agilent FieldFox N9916A vector network analyzer. The fabricated prototype and measured return loss are presented in Figs. 7(a) and 7(b), respectively. Fig. 7(c) presents the measured VSWR plot with experimental setup in inset, and the comparison between simulated and measured VSWR is depicted in Fig. 7(d). The measured impedance bandwidth (VSWR < 2) is about 50 MHz (2%) covering Wi-Fi and ISM wireless communication bands, whereas simulated bandwidth is about 76 MHz.

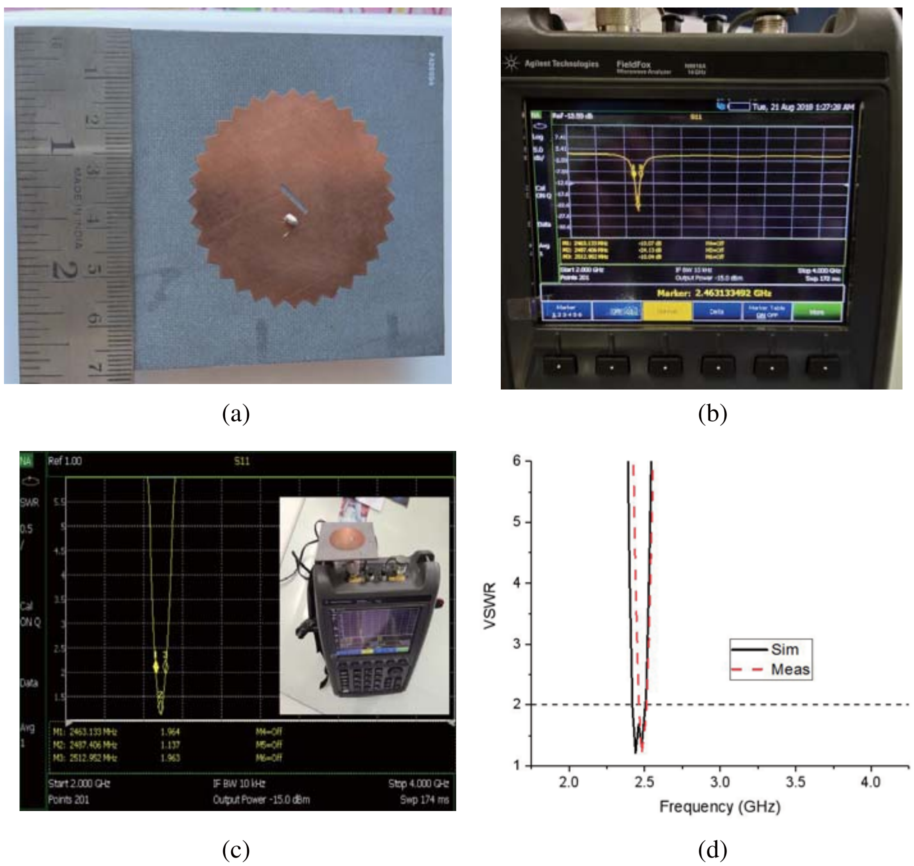


Figure 7. (a) Fabricated prototype. (b) Measured return loss. (c) Measured VSWR with experimental setup in inset. (d) Comparison between simulated and measured VSWR plot.

5. CONCLUSION

In the proposed research work, a unique saw-tooth shaped sequentially rotated fractal boundary square microstrip patch antenna for wireless application is presented and discussed. The designed antenna exhibits left hand circular polarization characteristics having 20 MHz of axial ratio bandwidth. The antenna offers 50 MHz of measured impedance bandwidth with 7 dBi peak gain in broadside direction. The simulated and measured VSWR results of proposed fractal antenna are in close agreement covering Wi-Fi and ISM wireless communication applications.

ACKNOWLEDGMENT

Mandar P. Joshi is highly indebted to Management and Principal of G.E.S's R. H. Sapat College of Engineering, Management Studies and Research, Nashik (MS), India for allowing him to pursue Ph.D.

under Savitribai Phule Pune University, Pune, India. Technical support of Roger's Corporation, USA and Sonic Multitech Pvt. Ltd, Nashik, India is thankfully acknowledged.

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