International Journal of Microwave and Wireless Technologies

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Research Paper

Cite this article: Aggarwal M, Pharwaha APS (2021). Modified Koch curve broadband fractal antenna for spectrum sensing in cognitive radio. *International Journal of Microwave and Wireless Technologies* **13**, 947–953. https://doi.org/10.1017/S1759078720001592

Received: 15 September 2019
Revised: 3 November 2020
Accepted: 4 November 2020
First published online: 3 December 2020

Key words:
Cognitive radio; fractal; Koch curve; spectrum sensing

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Modified Koch curve broadband fractal antenna for spectrum sensing in cognitive radio

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Abstract

This paper presents the design and development of broadband modified Koch curve microstrip patch antenna with multiband characteristics for spectrum sensing in cognitive radio applications. The proposed spectrum sensing antenna is designed specifically for its efficient operation in the spectrum (1.683–3.05, 4.246–9.714, and 11.25–18 GHz) specified for L, S, C, X, K_u with broadband characteristics and omnidirectional radiation pattern. The validity of the proposed shape is proved by having a comparison with other fractal shapes available in the literature.

Introduction

To fulfill the requirement of small-sized antenna for modern wireless communication, the microstrip antenna with a metallic patch fabricated on a dielectric substrate with ground plane either on the opposite side or same side [1] can be used. These antennas are low profile, simple, cost-effective, and conformable to planar as well as non-planar surfaces [2]. The flexibility, as well as the versatility of the antenna structures, can be further increased by using different feeding techniques [3]. Incorporation of fractal geometries further makes their size compact [4, 5]. The space-filling property of the fractals results into a compact size. The self-similarity property further facilitates these antennas to have multiband as well as wideband characteristics [6, 7]. The performance parameters of these antennas further can be improved by inserting slots in the ground plane [8]. Soft computing methods can be applied to improve the performance parameters of the antenna [9, 10]. Cognitive radio is an aware and adaptive radio with the reconfigurable front end [11]. These systems endlessly sense the spectrum and communicate within the free band. A wideband antenna with omnidirectional radiation pattern is necessary for spectrum sensing [12] in cognitive radios. In [13] a slotted disc UWB antenna for spectrum sensing is presented for a frequency range of 0.7–11.23 GHz with large size of $150 \times 120\,mm^2$ with quasi-omnidirectional radiation pattern. In [14] Sierpinski triangular fractal geometry is presented leading to the simulation covering 8–12, 12–18 and 18–26.5 GHz bands for spectrum sensing in cognitive radio but with simulated results only. In [15] a UWB antenna is proposed for the frequency range of 1.35-more than 30 GHz but with non-omnidirectionality in radiation pattern and with simulated results only. In [16] an E-shaped fractal antenna is designed for spectrum sensing in cognitive radios with a multiband response in 0.9–4 GHz frequency range, but only simulated results are provided. In [17] integrated sensing and communicating antenna is proposed for cognitive radios in which sensing antenna is having a bandwidth from 2 to 5.5 GHz with dimensions of $80 \times 65\,mm^2$, the radiation pattern is quasi-omnidirectional. In [18] a frequency reconfigurable integrated antenna for cognitive radio application is presented for the frequency range of 2–12 GHz with a size of $60 \times 60\,mm^2$. In [19] a microstrip modified Koch fractal antenna for cognitive radio applications is presented with four resonant frequencies 3.2, 5.2, 6, and 9.5 GHz which is having small size as compared to proposed geometry but with narrow bandwidth. Keeping in mind the requirement of spectrum sensing antenna and limitations of small bandwidth with large size and non-omnidirectionality of literature available, a modified shape of the Koch curve antenna is designed with wideband characteristics in three bands with omnidirectional radiation pattern. Furthermore, the ground plane is miniaturized by inserting a slot in the ground plane and Moth flame optimization (MFO) [20] is applied to optimize the ground plane.

Proposed fractal antenna design

Antenna design

Geometrical details of the proposed modified Koch curve antenna are presented in Fig. 1. The generator is a long wire of width (W) 80 mm and strip width (t) 1 mm. In the first iteration, the generator is divided into four equal parts and a trapezoidal is made with indentation angle

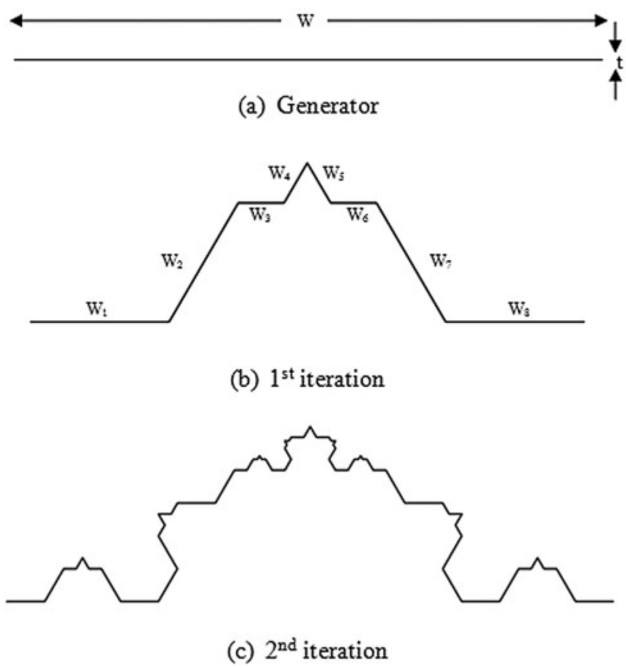

Fig. 1. Geometrical description of the proposed design: (a) generator, (b) first iteration, (c) second iteration.

$\theta = 60°$ on central two parts. Then a Koch curve technique is applied with indentation angle 60° on top of the trapezoidal. In the second iteration, the same shape is repeated on every segment of the first iteration. Microstrip feed with a width of 2 mm and length 19 mm is used. FR4 material with dielectric constant $\epsilon_r = 4.4$, the height of substrate $h = 1.6$ mm and loss tangent $\delta = 0.02$ is used for the design of the antenna. The copper cladding of 35 µm, over the substrate, is used for fabrication.

The proposed modified Koch fractal antenna is generated using iterated function system (IFS) with the help of a set of affine transformations having $\theta = 60°$ shown by Table 1. Fractal geometry is obtained by repeatedly applying affine transformation W_1, W_2, W_3, …, W_8 given by equation (1)

$$W(x, y) = \bigcup_{n=1}^{8} W_n(x, y) \tag{1}$$

In Fig. 2, various iterations of the proposed design are presented and its dimensional parameters are given in Table 2. In Fig. 2(d), a $3 \times 4\ \text{mm}^2$ slot is inserted in the ground plane to get miniaturized shape.

MoM-based IE3D software is used for designing the geometry. IE3D is a full-wave electromagnetic and optimization package. Figure 3 shows the S_{11} parameters of the antenna for various iterations. It has been observed from the graph that impedance matching improves in the second iteration in Bands I and II. In the first iteration lower cut off frequency is 1.854 GHz and in the second iteration, it is shifted to 1.769 GHz. In miniaturized shape, it is again at 1.854 GHz but with very good impedance matching in Bands III and IV. There is an existence of four bands after miniaturization as shown in Fig. 3.

Optimization of proposed fractal antenna

MFO is applied on the width of the ground plane of the proposed design. It is inspired by the navigation method of moths in nature called transverse orientation. The objective function for MFO is computed using polynomial curve fitting method in MATLAB environment as described in equation (2). The main aim is to find the value of ground width "*a*" of Fig. 2(c), to attain reflection coefficient *f(z)* below −10 dB for frequencies lies between Bands II and III.

Objective function = min *f(z)*
where

$$z = 1.49\,y^5 + 1.21\,y^4 - 3.1y^3 - 3.85y^2 - 2.72y - 14.54 \tag{2}$$

and $y = (x - 10.182)/3.6$, x is the variable used for different values of ground width "*a*".

Table 3 depicts the optimized value of width "*a*" and corresponding geometry is shown in Fig. 4. After optimization, Band I gets broader to 1.683–3.05 GHz. Band II (4.417–6.211 GHz) and Band III (7.065–9.543 GHz) got merged into the single band (4.246–9.714 GHz), which clearly shows merging of both bands as well as the extension of both lower and upper cut-off frequencies. Frequency range of Band IV i.e. (11.68–17.57 GHz) becomes (11.25–18 GHz) with optimization as shown in Fig. 5.

Table 1. IFS generator equations for proposed geometry.

$W_1\begin{pmatrix}x\\y\end{pmatrix} = \begin{bmatrix}\frac{1}{4} & 0\\ 0 & \frac{1}{4}\end{bmatrix}\begin{pmatrix}x\\y\end{pmatrix} + \begin{bmatrix}0\\0\end{bmatrix}$	$W_2\begin{pmatrix}x\\y\end{pmatrix} = \begin{bmatrix}\frac{1}{8} & -\frac{\sqrt{3}}{8}\\ \frac{\sqrt{3}}{8} & \frac{1}{8}\end{bmatrix}\begin{pmatrix}x\\y\end{pmatrix} + \begin{bmatrix}\frac{1}{4}\\0\end{bmatrix}$
$W_3\begin{pmatrix}x\\y\end{pmatrix} = \begin{bmatrix}\frac{1}{12} & 0\\ 0 & \frac{1}{12}\end{bmatrix}\begin{pmatrix}x\\y\end{pmatrix} + \begin{bmatrix}\frac{3}{8}\\ \frac{\sqrt{3}}{8}\end{bmatrix}$	$W_4\begin{pmatrix}x\\y\end{pmatrix} = \begin{bmatrix}\frac{1}{24} & -\frac{\sqrt{3}}{24}\\ \frac{\sqrt{3}}{24} & \frac{1}{24}\end{bmatrix}\begin{pmatrix}x\\y\end{pmatrix} + \begin{bmatrix}\frac{11}{24}\\ \frac{\sqrt{3}}{8}\end{bmatrix}$
$W_5\begin{pmatrix}x\\y\end{pmatrix} = \begin{bmatrix}\frac{1}{24} & \frac{\sqrt{3}}{24}\\ -\frac{\sqrt{3}}{24} & \frac{1}{24}\end{bmatrix}\begin{pmatrix}x\\y\end{pmatrix} + \begin{bmatrix}\frac{1}{2}\\ \frac{\sqrt{3}}{6}\end{bmatrix}$	$W_6\begin{pmatrix}x\\y\end{pmatrix} = \begin{bmatrix}\frac{1}{12} & 0\\ 0 & \frac{1}{12}\end{bmatrix}\begin{pmatrix}x\\y\end{pmatrix} + \begin{bmatrix}\frac{13}{24}\\ \frac{\sqrt{3}}{8}\end{bmatrix}$
$W_7\begin{pmatrix}x\\y\end{pmatrix} = \begin{bmatrix}\frac{1}{8} & \frac{\sqrt{3}}{8}\\ -\frac{\sqrt{3}}{8} & \frac{1}{8}\end{bmatrix}\begin{pmatrix}x\\y\end{pmatrix} + \begin{bmatrix}\frac{5}{8}\\ \frac{\sqrt{3}}{8}\end{bmatrix}$	$W_8\begin{pmatrix}x\\y\end{pmatrix} = \begin{bmatrix}\frac{1}{4} & 0\\ 0 & \frac{1}{4}\end{bmatrix}\begin{pmatrix}x\\y\end{pmatrix} + \begin{bmatrix}\frac{3}{4}\\0\end{bmatrix}$

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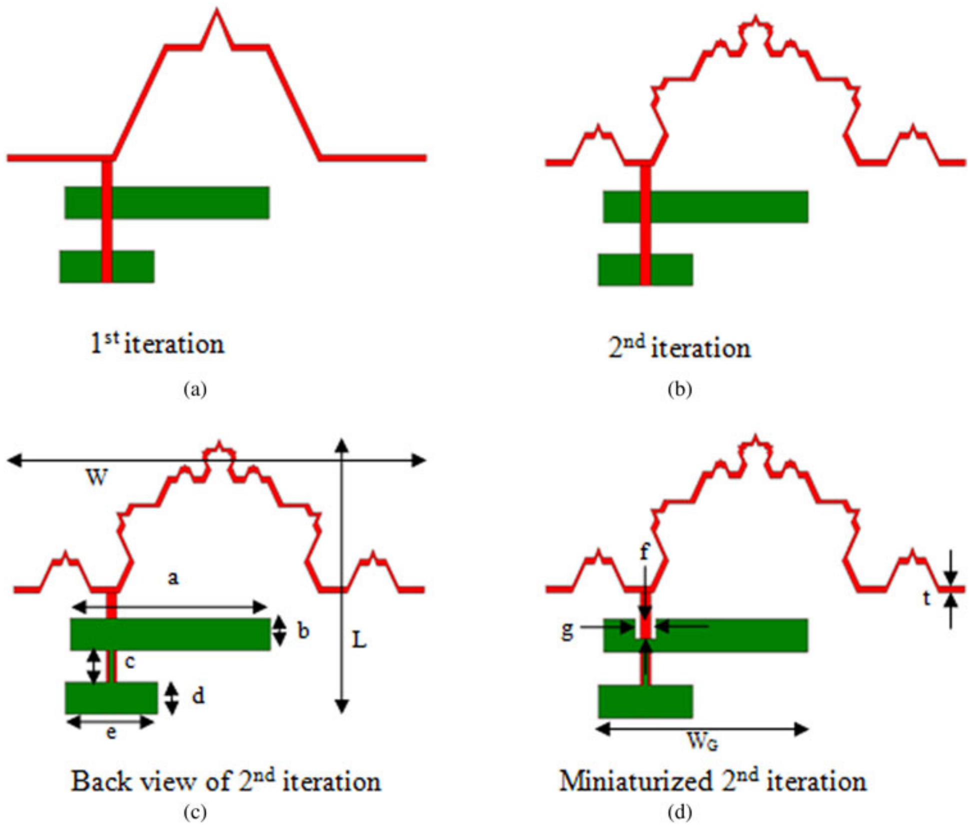

Fig. 2. Iterations of the proposed design: (a) first iteration, (b) second iteration, (c) back view of the second iteration, (d) miniaturized second iteration.

Table 2. Dimensional parameters of the antenna

Dimension	*W*	*L*	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*t*	W_G
Corresponding value (mm)	80	43.1056	39	5	5	5	18	3	4	1	40

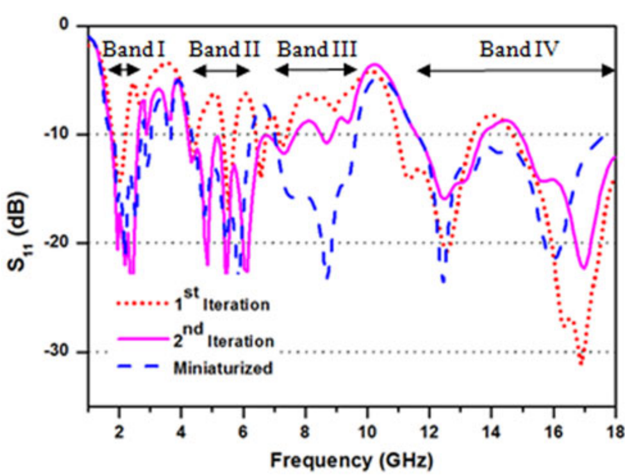

Fig. 3. S_{11} of modified Koch curve with various iterations.

Fabrication of the proposed fractal antenna

The proposed design using modified Koch curve fractal geometry is validated after obtaining the optimized results and fabricating the antenna in the form of a patch on a double-sided FR4 copper clad board using printed circuit technology as shown in Fig. 6. A

Table 3. Dimension obtained after optimization

Ground width "*a*" without optimization (mm)	Δ*x* (mm)	Ground width "*a*" after optimization (mm)
39	−3.62	35.38

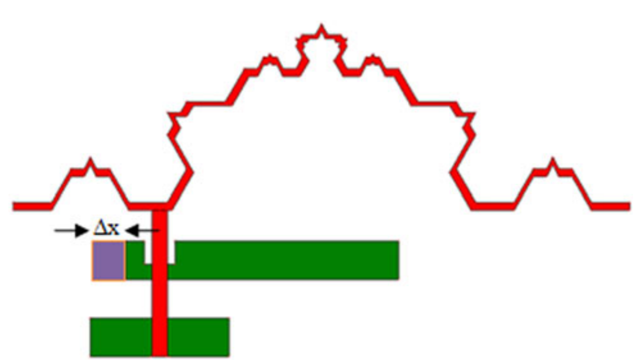

Fig. 4. Optimized geometry of the proposed design.

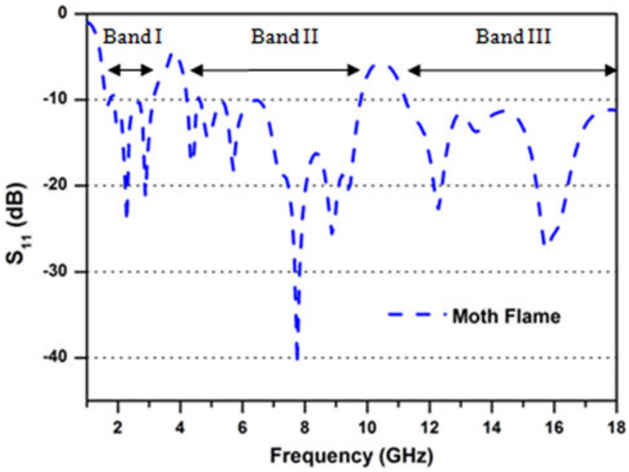

Fig. 5. S_{11} after optimization.

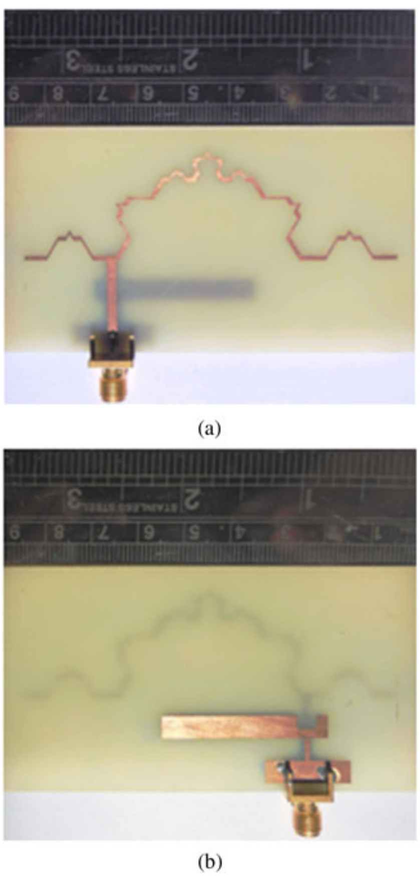

Fig. 6. Fabricated antenna: (a) front view, (b) back view.

50 Ω SubMiniature version A (SMA) edge mount female connector is used with microstrip feed and ground plane to achieve experimental observations.

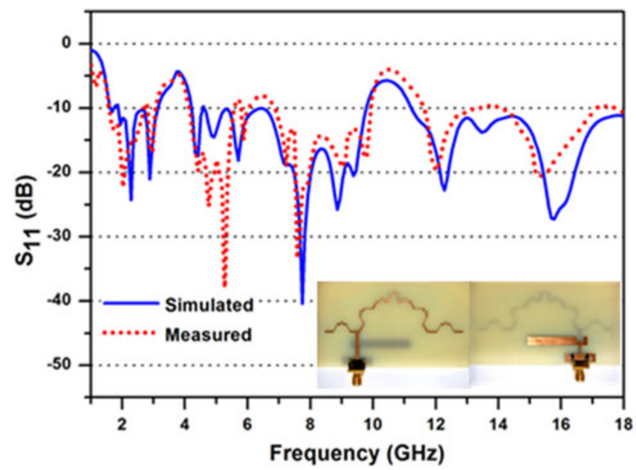

Fig. 7. Simulated and measured S_{11} of the proposed design.

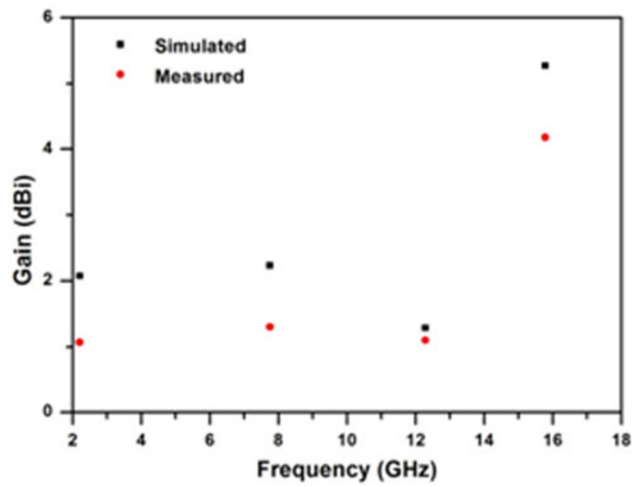

Fig. 8. Simulated and measured gain of the proposed design.

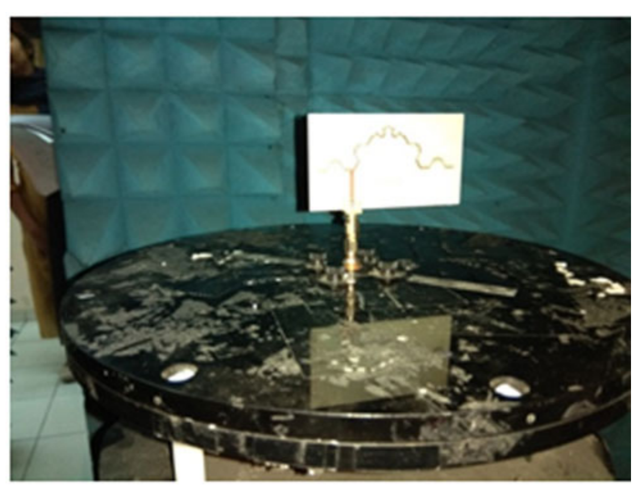

Fig. 9. Fabricated antenna in anechoic chamber.

Results and discussion

Simulated and measured S_{11}

Experimental validation of the proposed fractal antenna is carried out by having a comparison of simulated and measured S_{11} from the fabricated antenna. Vector network analyzer was used for making measurements on the fabricated antenna. The simulated and measured results are compared for concluding its actual

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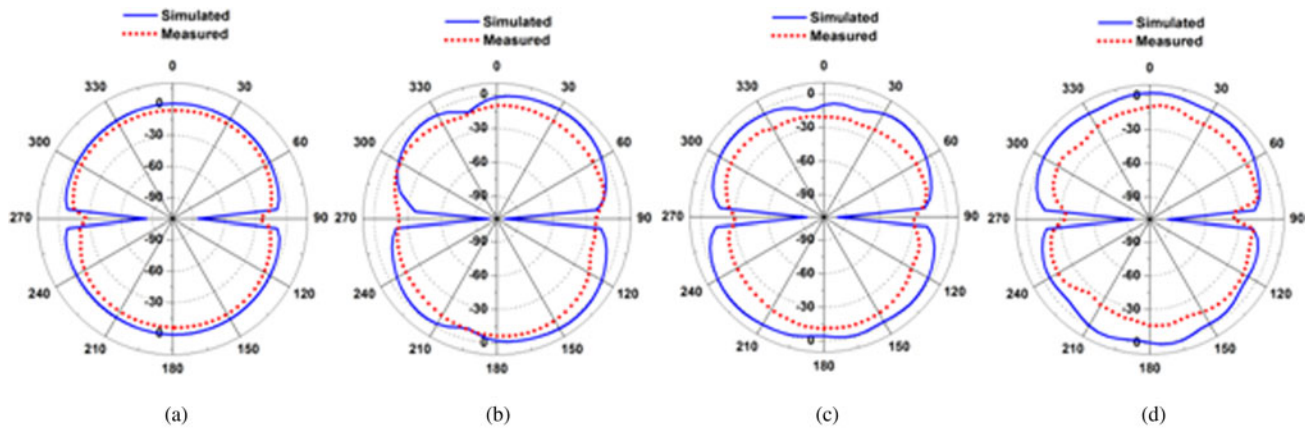

Fig. 10. Normalized polar plots for *E*-plane at (a) 2.2 GHz, (b) 7.75 GHz, (c) 12.28 GHz, (d) 15.78 GHz.

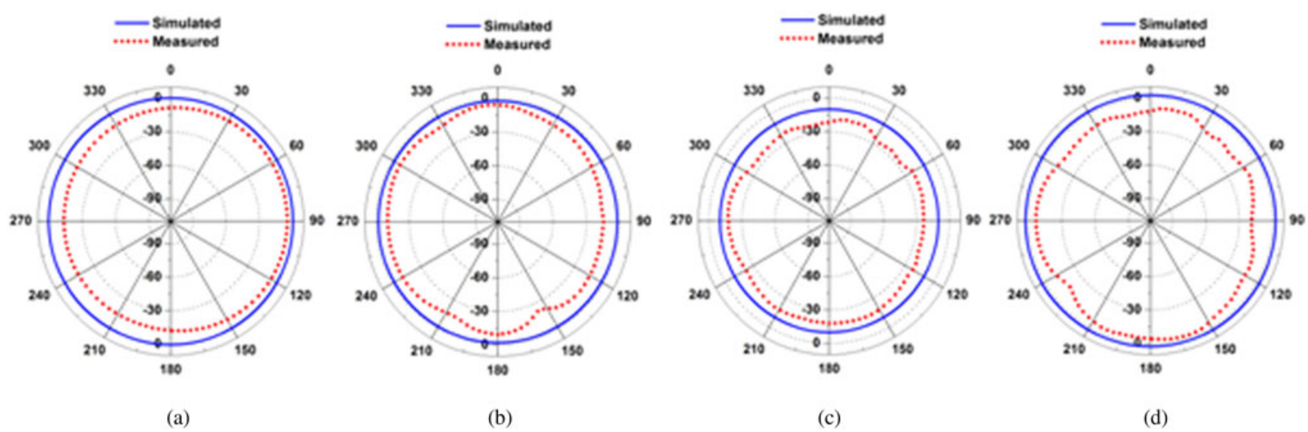

Fig. 11. Normalized polar plots for *H*-plane at (a) 2.2 GHz, (b) 7.75 GHz, (c) 12.28 GHz, (d) 15.78 GHz.

performance. The value of the corresponding S_{11} is measured at different frequencies of its operation in the specified bands. The graph obtained in Fig. 7 reveals that there is a good similarity in the simulated and measured outcome pertaining to the proposed bands at low frequencies. A slight deviation in measured S_{11} is observed which is due to lot of factors like fabrication tolerances as well as experimental errors during real-time measurements.

Gain versus frequency

Figure 8 depicts the simulated and measured gain of the proposed design at various frequencies of the proposed band. The antenna is kept at a distance of 2 m from reference antenna (Horn antenna). The simulated value of gain is 2.08, 2.24, 1.29, and 5.27 dBi and a measured value of the gain is 1.067, 1.304, 1.102, and 4.181 dBi at 2.2, 7.75, 12.28, and 15.78 GHz, respectively.

Radiation pattern

Figure 9 presents the fabricated antenna mounted in an anechoic chamber in front of the reference antenna for real-time measurements. Figures 10 and 11 indicate the simulated and measured radiation pattern of the proposed fractal antenna in elevation and azimuth planes, respectively, after having the optimization of the proposed geometry. The radiation pattern is directional in elevation plane and non-directional in the azimuth plane, which confirms to the fact that the radiation pattern is omnidirectional, which of course is the fundamental requirement of the spectrum sensing antenna in cognitive radio applications. A small variation is observed at high frequency in *E*-plane and *H*-plane. Apart from that, there is good matching in the simulated and measured results which further proves the validity of the proposed design.

Table 4 presents the comparison of antenna available in the literature with the proposed antenna and it has been observed that proposed antenna is having smaller dimensions and broad bandwidth as compared to many other available fractal antennas of comparable size. In the literature most of the antennas are narrowband but the proposed shape is broadband. Copper required for the proposed shape is also very less.

Conclusion

A modified Koch curve patch antenna has been developed for spectrum sensing in cognitive radio having the operation in three bands 1.683–3.05 GHz (57.7%), 4.246–9.714 GHz (78.33%), 11.25–18 GHz (46.15%) with broadband characteristics and omnidirectional

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Table 4. Comparison of the proposed antenna with other fractal antennas in literature

Reference	Geometry	Substrate material	Dimension (mm^2)	Bandwidth (GHz)	Year of publication
[21]	Nano arm fractal	FR4 ($\varepsilon_r = 4.3$)	63.5 × 65	2.55–11.84	2013
[22]	Sierpinski monopole gasket	Arlon ($\varepsilon_r = 3.2$)	83.5 × 50.5	1.1, 3.4, 5.8	2014
[23]	Hexagonal fractal antenna	Epoxy Woven glass ($\varepsilon_r = 4.6$)	60 × 80	1.34–3.44	2015
[24]	Koch geometry on the edges of a square patch	FR4 ($\varepsilon_r = 4.4$)	60 × 55	4.3, 5, 6.1 ,7.4, 8.9, 9.2	2018
[25]	Square patch with square loop	FR4 ($\varepsilon_r = 4.4$)	80 × 80	0.79, 1.79, 2.14, 2.45, 3.4, 5.3	2017
[26]	Coin-shaped fractal antenna	FR4 ($\varepsilon_r = 4.4$)	88.5 × 60	1.43–2.84, 3.37–3.99, 4.51–5.53	2017
[27]	LSA with modified Koch curve	RT duroid 5870 ($\varepsilon_r = 2.33$)	53 × 58	2.0–18.30 (with $\lvert S_{11} \rvert < -5$ dB)	2018
[28]	Flexible fractal antenna	FR4 ($\varepsilon_r = 4.4$)	97.48 × 80	2.20–2.61, 3.38–3.98	2018
[29]	Modified Minkowski fractal	FR4 ($\varepsilon_r = 4.4$)	118 × 60	0.496–1.06, 1.45, 2.09, 2.38, 3.23, 3.79, 4.06, 4.35, 4.65, 4.82, 5.24, 5.62, 6.12	2018
[30]	Koch fractal boundary slot antenna	FR4 ($\varepsilon_r = 4.4$)	100 × 100	1.8–3.40	2018
[31]	Sierpinski square patch	Arlon ($\varepsilon_r = 2.5$)	115 × 115	1.575	2019
Proposed	Modified Koch	FR4 ($\varepsilon_r = 4.4$)	43.1 × 80	1.68–3.05, 4.24–9.71, 11.25–18	-

radiation pattern. Comparison of simulated results with the measured results is done to validate the performance of the proposed design. The antenna is fabricated with 1.6 mm thick FR4 substrate ($\epsilon_r = 4.4$ and $\delta = 0.02$). The presented approach has a potential future in the development of spectrum sensing patch antennas for cognitive radio applications in other bands as well.

Acknowledgements. The authors are grateful to Prof. (Dr.) Shailendra Jain, Director, Sant Longowal Institute of Engineering & Technology (SLIET), Longowal-148106, District Sangrur, Punjab, India for his continuous support and encouragement during the present work. They also acknowledge the excellent technical support extended by the Department of Electronics and Communication Engineering, SLIET, Longowal as well as IIT Delhi to complete experimental work on Vector Network Analyzer and Anechoic Chamber.

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