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RESEARCH ARTICLE

On the Development of Compact Super-Wideband Fractal Antenna

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Abstract

Objective: To design and fabricate a compact fractal antenna with high Bandwidth Ratio (BR) and Bandwidth Dimension Ratio (BDR) for Super-Wideband (SWB) and upcoming wireless communication applications. **Methods:** High Frequency Structure Simulator (HFSS) is used for all the required simulations regarding antenna prototype design and optimization. The proposed antenna consists of nested square fractal in a circular ring and with a rounded corner notch loaded partial ground, which is designed and fabricated on 1 mm thick FR4 substrate. **Findings:** The final results evince that proposed antenna has an operating bandwidth of 36.5 GHz (2.37- 38.95 GHz), with a reflection coefficient (S_{11}) less than -10 dB. It has a maximum gain of 13.4 dBi, BDR of 3498, and BR of 16.4:1. It has an Electrical dimension of $0.22 \times 0.23\,\lambda^2$. The proposed antenna's resonating and radiation characteristics have been validated experimentally. Simulated and experimentally measured results are in good agreement with each other. **Novelty:** The key benefits of the proposed antenna are small electrical dimensions, large bandwidth, and a high BDR. The proposed antenna is suitable for numerous wireless applications such as WLAN, WiMAX, Wi-Fi, 5G communication in sub-6Ghz band as well as in mm Wave frequency band, and S, C, X, Ku, and Ka bands applications.

Keywords: Bandwidth Dimension Ratio; Compact; Electrical Dimension; Nested Square Fractal; Super-wideband

1 Introduction

In recent research studies, the wideband patch antennas are more popular in the numerous wireless applications as these offer super wide bandwidth, compact in size, easy integration with other devices, and simple in design [1]. A frequency range from 3.1- 10.6 GHz is allotted for Ultra-Wide Band (UWB) technology by Federal Communications Commission in 2002 [2,3]. Since then, various antennas were proposed for UWB technology due to its attractive features. Wideband characteristics of antenna are very useful for various defense, medical and commercial applications[4–6]. Parallel with exponentially developing wireless system technologies towards next generation communication, there is a continuous rise in demand for high spectral efficiency, multifunctional, good radiation characteristics, compact in size, and high rate of data transfer. Although UWB technology have been utilized in various application to fulfill these requirements but in spite of high BR of 3.4:1, they are not suitable for long distance communication because of their long signal acquisition time, slow adaptation rate, and low power transmission[7–10]. Thus, to satisfy the interest in both long-range and short-range communication, researchers have begun efforts to implement SWB technology in wireless devices. Rumsey proposed the notion of SWB antenna technology in 1966[11]. The frequency range for UWB technology is defined by FCC but frequency range for SWB technology is not predefined. An antenna can be considered a SWB antenna if it has a BR of 10:1 for S_{11} less than -10 dB over the entire operating frequency range. Besides all the attractive features like: high data rate, high channel capacity, high BR, and high resolution, designing a SWB antenna is a challenging and difficult task.

A large number of microstrip patch antenna with SWB characteristics were investigated by researcher in recent past[10–28] A concentric structured monopole compact patch antenna is proposed in[10], for SWB application. Electrical dimension of this antenna is $0.18 \times 0.16\lambda^2$ and it operates from 1.22 to 47.5 GHz. In[12], a patch antenna having a offset elliptical structure is presented for SWB applications. It has an operating bandwidth from 2.31- 40 GHz and has a BDR of 1732. In[20], a staircase fractal curve patch antenna is proposed for Super Wide Band (SWB) operation. it exhibits an impedance bandwidth ranging from 0.1-30 GHz. In[21], a Sierpinski SWB fractal antenna is presented that is fed by an asymmetrical feedline and have an impedance bandwidth of 3.87–35 GHz. In[22], a patch antenna with Clown-shape is presented with SWB characteristics. RT/Duroid 5880 of size $0.256 \times 0.266\ \lambda^2$ is used as substrate for the proposed antenna and it operates from 2.96- 100 GHz with a BDR of 2768. In[23], an antenna with three layer substrate is proposed with SWB features that operates in 2.2–22 GHz frequency range, with 97 % minimum efficiency of radiation and 5.2 dBi maximum gain. It has a BDR of 1755. In[24], a novel SWB antenna on flexible substrate Ultralam 3850 is investigated and designed that operates from 1.74 to 100 GHz. The antenna has a size of $60 \times 40 \times 0.1$ mm^3 and BR of 57.47:1. In[26], a compact SWB antenna is presented with enhanced bandwidth. Its structure is a fusion of circular slot, square slot and trapezoidal slot on the rectangular radiator with a defected ground. Its operating range is from 0.7- 18.5 GHz. The proposed antenna is useful for various applications in a wide range of UWB, K and Ku band portable devices. In[27], a SWB antenna is proposed which has an octagonal-ring shaped structure of radiator with a stub located on the top right corner of it to improve the operating impedance bandwidth. It covers the frequency range from 2.59-31.14 GHz with $S_{11} \leq -10$ dB, and bandwidth ratio of 12.02:1. These antennas have issues such as less BR, low BDR, low fractional bandwidth, and large electrical dimensions. The major challenge in designing such a type of SWB antenna is achieving compactness in antenna design keeping the operating bandwidth extremely high at the same time. To get smaller electrical dimensions fractal geometries can be incorporated into radiating elements as it helps in antenna miniaturization. The incorporation of fractal geometries in radiating elements increases the impedance bandwidth and radiation characteristics of the antenna[13,29] Many researchers designed antenna using fractals like: Koch, fractal tree, hexagonal-triangular fractal, Sierpinski fractal, and octagonal fractal in past[30–34] This work has been done to overcome the above challenges while keeping the electrical dimensions of the antenna small and compact in size.

In this work, a compact SWB antenna with high BDR nested square fractal shaped is designed and validated. A bandwidth of 36.58 GHz ranging from 2.37 GHz to 38.95 GHz is achieved by using fractal geometry in a circular ring, tapered feed line, and corner rounded ground. It has a bandwidth of 36.58 GHz, BR of 16.4:1, a maximum gain of 13.4 dBi, and high BDR of 3498. The proposed antenna is designed and analyzed using ANSYS HFSS software.

This paper is divided into four sections: Section II contains the methodology; Section III presents the experimental results and section IV summarizes the conclusion.

Table 1. Dimensional details of the proposed SWB antenna

Parameter	Value (mm)	Parameter	Value (mm)
SubW	28	S1	11.6
SubL	30	S2	7.6
Gnd W	28	S3	4.8
Gnd H	8.2	FL	9
Ro	8.5	FW	2
Ri	7.5	PPS	3.6
Sw	0.5	GSS	2

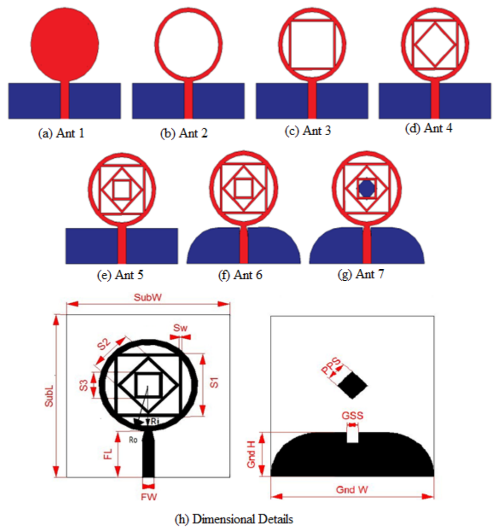

Fig 1. All stages of the antenna geometry with dimensional details

2 Methodology

The ANSYS HFSS software has been used to design and analyze the proposed structure of antenna. All different stages of the proposed design structure of antenna has been shown in Figure 1 from image (a)-(g) and image (h) shows the dimensional details of the proposed design. All dimensional details of the antenna have been mentioned in Table 1. It is fabricated on FR4 substrate which has a dielectric constant of 4.4, tan δ=0.02 and a thickness of 1 mm. In first stage, a circular patch antenna has been designed as shown in Figure 1 (a) and further investigated. The dimension of the circular patch antenna has been calculated using the equation (1)[8].

$$f_L = \frac{7.2}{(L+r+p)\times k} GHz \tag{1}$$

Where, f_L is the lower cut-off frequency of the operating bandwidth, L=2R_0 is the height of planar patch antenna, r= R_0/4 is the effective radius of equivalent cylindrical patch antenna, and p= FL-GndH is the gap between radiating element and ground plane all are in centimeters. For FR4 dielectric substrate k is 1.15. The feed width (FW) of feedline for initial design is calculated using the equation (2)[8]given below:

$$FW = \left[\frac{8\times e^A}{e^{2A}-2}\right]\times h \tag{2}$$

Here h is the substrate height and value of A is calculated using equation (3).

$$A = \frac{Z_0}{60}\left(\frac{\varepsilon_r+1}{2}\right)^{1/2} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23+\frac{0.11}{\varepsilon_r}\right) \tag{3}$$

The antenna structure has an electrical dimension ion of 0.22 × 0.23 λ^2. In the current analysis of the first stage, it is found that the current density in the central part of the circular radiating element is negligible, and its S_{11} shows that its matching is also not good, so its middle part is etched out in Ant2, as shown in Figure 1 (b). 2nd Stage of the antenna is further modified and a nested square fractal is incorporated into it as shown in Figure 1 (c)(e). In 6th stage, to improve impedance matching top corners of ground plane have been circularly truncated also a rectangular notch has been loaded beneath the feed line in ground structure as depicted in Figure 1 (f). The S_{11} of Ant1 to Ant6 has been shown in Figure 2 (a). Ant 6 has a wide operating bandwidth but it has a notch near 16.6 GHz which is restricting antenna bandwidth. At this stage an analysis has been done to see the effect of changing the feed width on S_{11}. The feedline width is varied from 1.5–2.5 mm and its effect on S_{11} is shown in Figure 2 (b). After this parametric optimization the FW has been changed to 2 mm where the antenna has optimum performance in reference of S11. But it could not completely eliminate the notched band. So, a square parasitic patch has been used to completely remove the notch, which is placed under the radiation element as shown in Figure 1 (g) ant 7.

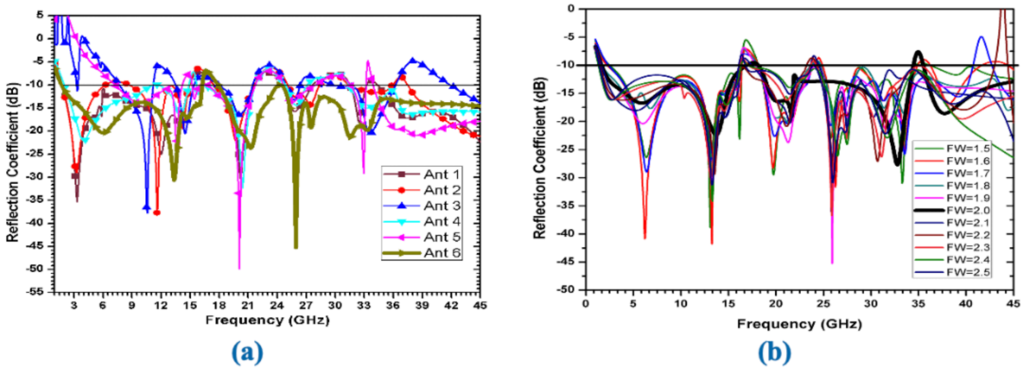

Fig 2. (a) S_{11} for Ant1 to Ant 6 design stages of antenna (b) S_{11} for different value of feed width at stage 6

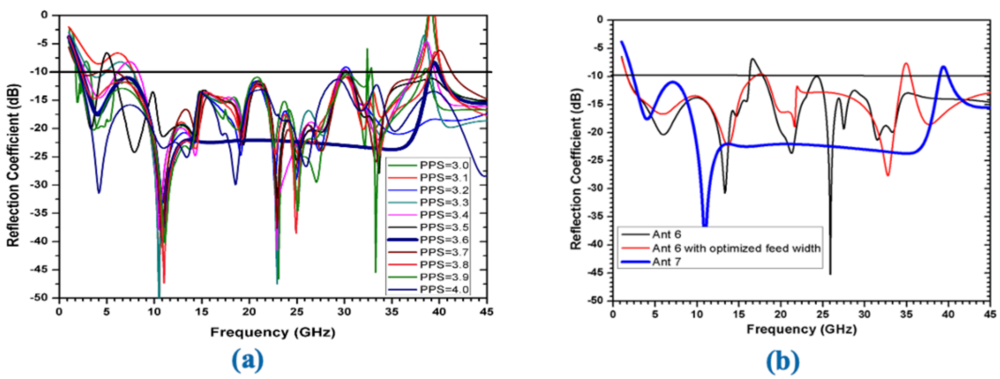

Fig 3. (a) S_{11} for different value of parasitic patch size at stage 7 (b) S_{11} for Ant 6 without and with optimization, and optimized Ant 7

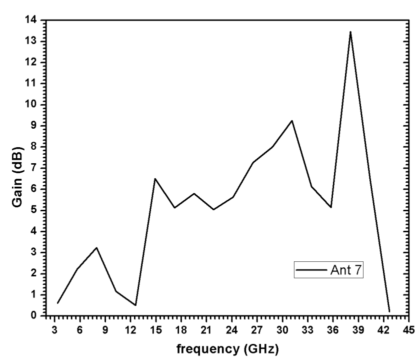

Fig 4. Gain of the proposed antenna

Parametric analysis has again been performed to select the optimal size of the parasite patch. The variation in s11 for different values of PPS is shown in Figure 3 (a). It can be analyzed from Figure 3 (a) that when the PPS is equal to 3.6, the Ant7 is very well matched and a super wideband is achieved from 2.37 to 38.95 GHz. The difference in S_{11} of Ant6, Ant6 with optimized feed width and Ant7 with optimized PPS size can be seen in Figure 3 (b). The optimized geometrical dimension details in mm of the proposed antenna are presented in Figure 1 (h). The final antenna design (Ant7) with the rounded ground, tapered feed, and parasitic square element provide the best performance in terms of matching with the lowest cut-off frequency of 2.37 GHz and highest of 38.95 GHz. Figure 4 shows the proposed antenna gain versus frequency plot and it is positive for entire operating range and has a maximum value of 13.4 dBi.

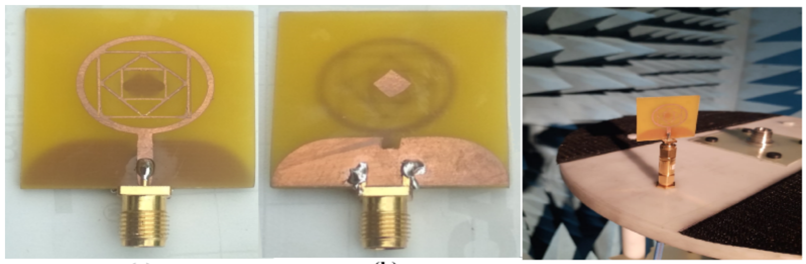

Fig 5. (a) Top View, (b) Bottom View of the antenna, and (c) antenna in anechoic chamber

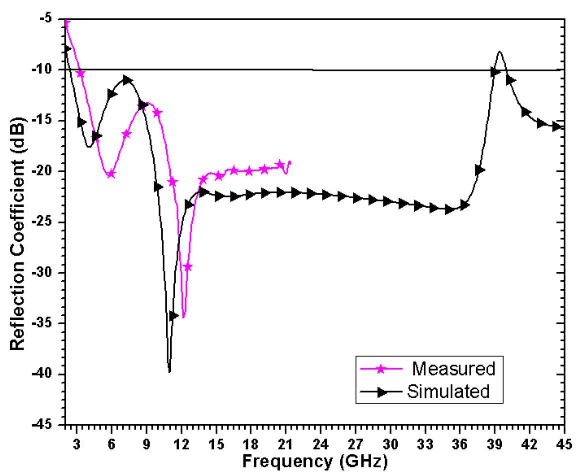

Fig 6. Measured andSimulated S_{11} of the proposed antenna

3 Results and Discussion

High-Frequency Structure Simulator (HFSS) has been used to design the antenna. The propose antenna design (Ant7) has been fabricated on FR4 substrate of size 30 x 28 x 1 mm^3. Both top and bottom view of the fabricated prototype are depicted in Figure 5. To verify the resonating and radiation characteristics of the proposed antenna, the fabricated antenna test has been carried out using KEYSIGHT PNA-L Network Analyzer N5232B. The measured reflection coefficient with simulated has been shown in Figure 6. Due to the limitation of resources the measurement has been carried out up to 20 GHz. The deviation present in measured results from simulated can be attributed to imperfect soldering, soldering bumps, fabrication, and measurement tolerances. Figure 7 shows the real and imaginary parts of input impedances. It can be observed from Figure 7 that the real part and imaginary part of input impedance is varying around about 50 ohms and 0 ohms respectively over the entire operating bandwidth which shows good matching performance. Figure 8 (a)-(c) shows the current distribution on the proposed structure at 4.08 GHz, 10.94 GHz, and 35.67 GHz. From Figure 8 (a), it is observed that at frequency 4.08 GHz the current density is higher on the circular ring and lower part of feedline structure. It is observed that the current density is high along the feedline, in the upper part of ground plane, and on the circular ring at 10.94 GHz as depicted in Figure 8 (b). It is observed from Figure 8 (c) that the current density is less in upper half-part of radiator and in the ground plane at 35.6 GHz.

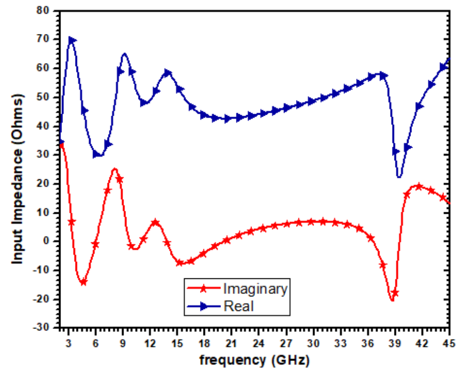

Fig 7. Real and Imaginary Input Impedance of the proposed antenna

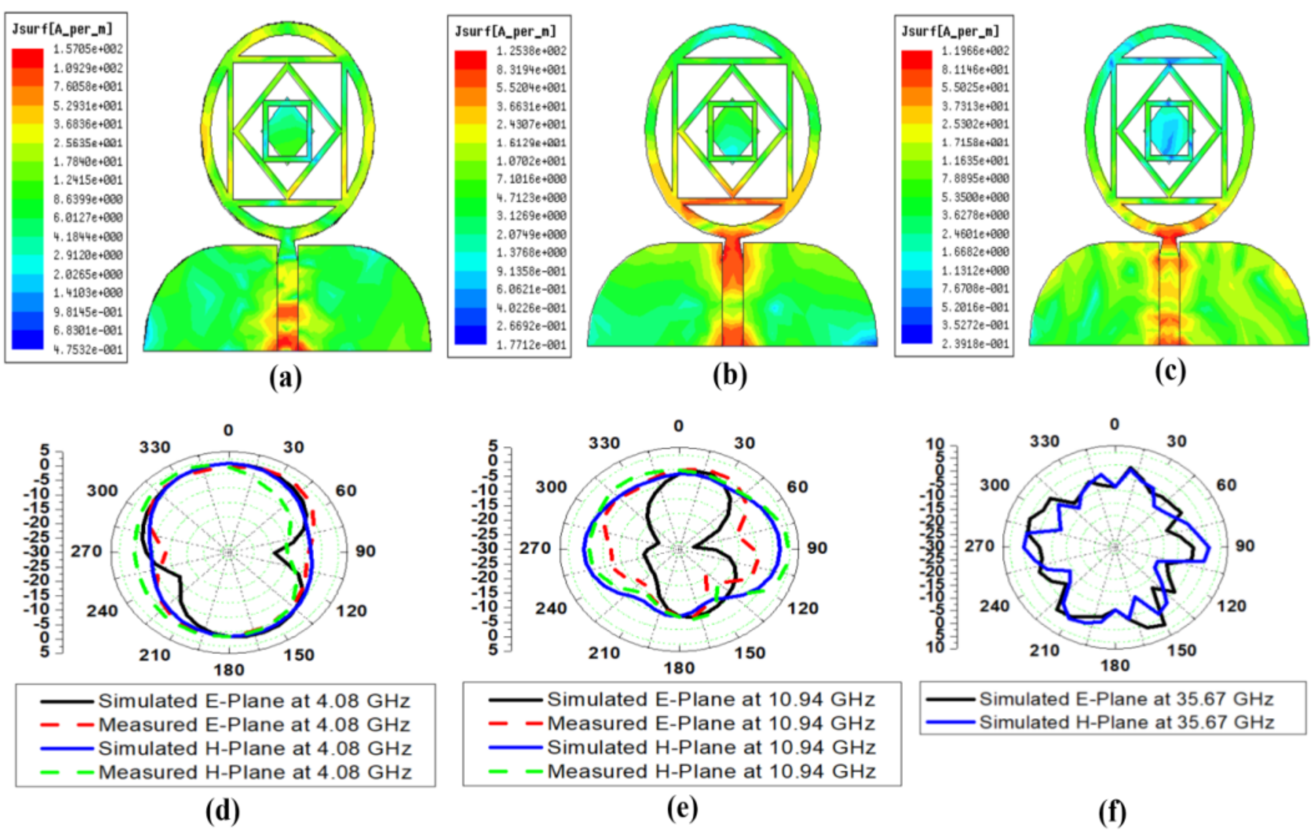

Fig 8. Surface current distribution and Radiation pattern at 4.08 GHz, 10.944 GHz, and at 35.672 GHz

It is proven from the distribution of current density over antenna structure that modes of higher order are excited at higher frequencies, resulting distortion of the radiation pattern at the higher frequencies. It can be depicted from Figure 8 that the

Table 2. Comparison of the proposed antenna with existing antennas

	Electrical Dimension	**BR:1**	**%BW**	**BDR**	$\mathbf{f_{Low}}$–$\mathbf{f_{high}}$ **(GHz)**
(8)	$0.27 \times 0.27\ \lambda^2$	15.13	175.20	2403.30	2.3-34.8
(12)	$0.33 \times 0.33\ \lambda^2$	34.63	188.56	1732	2.31 to 40
(13)	$0.34 \times 0.36\ \lambda^2$	15.47	175.72	1435.60	1.68-26
(14)	$0.32 \times 0.32\ \lambda^2$	13.00	171.62	1676.00	0.42-5.5
(15)	$0.30 \times 0.29\ \lambda^2$	11.30	167.49	1903.20	4.6-52
(16)	$0.27 \times 0.23\ \lambda^2$	10.00	164.00	2541.10	3.5-37.2
(17)	$0.30 \times 0.35\ \lambda^2$	14.28	173.8	1904.00	2.8 to 40
(18)	$0.25 \times 0.20\ \lambda^2$	5.72	140.56	2800	3.035 to 17.39
(19)	$0.28 \times 0.212\ \lambda^2$	13.79	172	2897	2.9 to 40
(27)	$0.34 \times 0.34\ \lambda^2$	12.02	169	1462	2.59 to 31.14
Proposed antenna	$0.22 \times 0.23\ \lambda^2$	16.40	177.00	3498.00	2.37-38.95

number of resonances increased with the increase in frequency. The radiation pattern of the antenna at 4.08 GHz, 10.94 GHz, and 35.67 GHz is depicted in Figure 8 (d)-(f). E-Plane patterns for all three frequencies are bidirectional and H-Plane patterns are Omnidirectional for all frequencies. However, the omnidirectional pattern becomes distorted at higher frequencies due to higher-order modes. The proposed antenna design has been compared with existing antennas in literature in terms of electrical dimension means compactness, fractional bandwidth, bandwidth, BR, and BDR. BDR shows the percentage operating bandwidth provided per unit electrical area. It is also a measure of the compactness of the antenna and can be represented as:

$$BDR = \frac{BW\%}{\lambda_{length} \times \lambda_{width}} \tag{4}$$

Where, λ is the wavelength with respect to the lowest operating frequency of the antenna. A higher BDR value validates the effectiveness of any antenna over other antennae.

In addition to that, the proposed antenna has been compared with existing antennas in Table 2 . It can be realized from table 2 that the proposed antenna is advantageous in terms of BDR and electrical dimension among all other tabulated antenna structure.

4 Conclusion

A compact SWB fractal antenna has been proposed with a nested square fractal structure. The proposed nested square fractal antenna is evolved from a conventional circular patch antenna. Its resonating and radiation characteristics were analyzed and validated experimentally. It has been observed that the measured results of the fabricated antennas are in good agreement with the simulated results which justify that the proposed antenna is suitable for SWB applications. Proposed antenna was compared with the existing antenna reported in literature and it was found that the proposed antenna is advantageous in terms of BDR and electrical dimension. Thus, it is useful for various wireless applications such as WLAN, WiMAX, Wi-Fi, 5G communication in sub-6Ghz band as well as in mmWave frequency band, and S, C, X, Ku, and Ka bands applications.

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