Compact Cauliflower-Shaped Antenna for Ultra-Wideband Applications

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Abstract – A compact coplanar waveguide (CPW) fed cauliflower-shaped antenna is presented and discussed in this paper. To extend the impedance bandwidth and to improve the impedance matching, fractal geometry having a cauliflower shape is introduced along the edges of the radiator. To validate the simulated results by experimental ones, a prototype of the designed antenna was fabricated on the RO-4350B substrate having a compact size of $0.3623\lambda_0 \times 0.41\lambda_0 \times 0.01524\lambda_0$ at 3 GHz. An Agilent 8722ES vector network was used for the reflection coefficient measurement revealing that the –10 dB bandwidth of the fabricated antenna offers an impedance bandwidth of 113% extending from 3.05 to 10.96 GHz. Besides, the antenna's radiation patterns are measured in an anechoic chamber showing consistent radiation patterns characteristic over the entire working band. Furthermore, the proposed antenna has a peak gain of around 6 dBi and an average radiation efficiency almost over 90% across the entire operating band. Thus, the proposed antenna could be useful in many modern ultra-wideband (UWB) communication systems.

Index Terms – Cauliflower-shaped antenna, coplanar waveguide (CPW) fed, hexagonal patch antenna, fractal geometry, ultra-wideband (UWB) antenna.

I. INTRODUCTION

In recent years, telecommunication systems have undergone significant technological change mainly due to the multiplication and growth of newer consumer markets. However, the emergence of the communication markets and the growth of the number of consumers have been accompanied by strict specifications to meet the requirements of the new users. Indeed, the new transmission/reception systems must today provide a maximum of services over different frequency bands and bit rates. The rise of planar technologies (microstrip, coplanar, etc.) for low-power applications is a part of the response to these new requirements. In these contexts, an ultra-wideband (UWB) technology has been purported as a promising solution for the new communication systems. UWB technology has many advantages, including high-speed transmission and low energy profile [1]. Since the definition of the frequency band from 3.1 to 10.6 GHz for UWB communication systems by the FCC in 2002 [2], several antenna structures have been reported by many researchers to enhance the bandwidth of the antennas [4–9].

However, the design of a UWB antenna presents various challenges to meet the different requirements: low profile, low cost, low radiated power, low power

consumption, broadband operability, high data rate transmission, and stable radiation patterns. Various solutions have been proposed to ensure these requirements; the most promising is the introduction of fractal geometries.

The use of these geometries increases the bandwidth and the gain and can introduce the multiband properties without changing the dimensions of the antenna which remains very compact. This allows us to produce miniature broadband antennas with performances similar to those of large antennas. Recently, many fractal structures have been proposed like those proposed in [10–18]. In [10], an antenna with Koch fractal geometry has been proposed to enhance the bandwidth. However, only 3.3 GHz (3-6.3 GHz) bandwidth has been achieved. A fractal antenna based on an octagonal patch and a semi-elliptical ground plane has been proposed in [11]. Unfortunately, this antenna has low gain which does not exceed 3 dBi and its efficiency is below 90% along the working bandwidth. More recently, in [12], a circular cross-slot AMC has been assembled with a fractal antenna to improve the bandwidth and the gain. The overall impedance bandwidth attained is 129.49% extending from 2.4 to 11.2 GHz. The main disadvantageous of the designed structure are the complexity and the large thickness which is about 9.4 mm. A novel wideband fractal antenna based on a hexagonal-circular geometry with large size of $80.6 \times 80.6 \times 1.6$ ^{3} has been proposed in [13]. The iterations of circular slots inside a hexagonal metallic patch have allowed to achieve a bandwidth of around 2 GHz extending from 1.34 to 3.44 GHz. A compact flexible fractal UWB antenna printed on a 12.5-μm flexible polyimide substrate has been presented in [14]. An impedance bandwidth of 15.48 GHz (3.6-19.08 GHz) has been achieved, but it suffers from a low gain which does not exceed 3.5 dBi along the interested frequency band. In [15], a hybrid of Sierpinski and Minkowski geometries has been exploited into a wide antenna for multiband applications. In [16], an antenna with Jerusalem crosses as fractal slots has been introduced to achieve wide bandwidth; no more than 0.6 GHz bandwidth with only 3.5 dBi peak gain and an efficiency value of 70% have been achieved at the resonating frequency. In [17], Minkowski fractal structures are introduced into a flexible antenna for improving the return loss and the impedance bandwidth. This flexible antenna that has been printed into large substrate ($97.48 \times 80 \times 0.5$ mm^3) is operating in two narrow bands with bandwidths < 0.6 GHz. Carpet geometry has been exploited in [18] for improving the bandwidth of a monopole antenna with defected ground structure. However, only 3.13 GHz bandwidth has been obtained.

In the present work, a cauliflower-shaped structure is exploited to achieve size-compactness and the UWB

response. The fractal geometry was introduced along the edges of the patch and on the outer corners of the truncated ground plane. A prototype was fabricated and measured showing a good concordance between the measured and the simulated results. The fabricated prototype has an impedance bandwidth of 7.91 GHz extending from 3.05 to 10.96 GHz and stable omni-directional radiation patterns. In addition, the simulated antenna has a reasonable gain (1.39-5.68 dBi) and high radiation efficiency ($>90\%$) values over the entire operating frequency band. The designed antenna was calculated and optimized by using the commercial software CST Microwave Studio$^{\text{TM}}$ [19]. The following section will present fractal length generations, describe the proposed antenna geometry, and depict the obtained results.

II. ANTENNA DESCRIPTION AND RESULTS
A. Process of antenna design

The proposed antenna is generated by combining the fractal concept and the hexagonal geometry. The geometrical configuration of this new fractal curve begins with a straight line, called the initiator, which is shown in Figure 1 (iteration 0). The first iteration divides the initial length into four equal parts, and the two centric segments are replaced by three other segments of the same length by forming a regular trapezoid with an angle $\theta = 60°$ as shown in Figure 1 (iteration 1). This iterative process is repeated for the higher-order iteration which is shown in Figure 1 (iteration 2).

Each segment of iteration 1 (generator) is one-fourth the length of the initiator. There are five such segments. Thus, for iteration n, the total length of the curve is $(5/4)^n$.
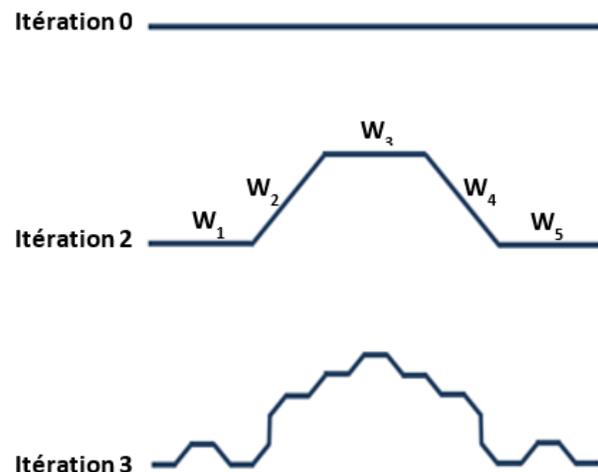
Fig. 1. Iteration-wise evolution of cauliflower-shaped structure.

B. Generating fractal geometry using iterative function system (IFS)

An IFS can be used to define the generator. The transformations used to obtain the generator segments are given by the following equations:

$$W_1 \begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} \frac{1}{4} & 0 \\ 0 & \frac{1}{4} \end{bmatrix} \begin{pmatrix} x \\ y \end{pmatrix}, \tag{1}$$

$$W_2 \begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} \frac{1}{4}\cos 60° & -\frac{1}{4}\sin 60° \\ \frac{1}{4}\sin 60° & \frac{1}{4}\cos 60° \end{bmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} \frac{1}{4} \\ 0 \end{pmatrix}, \tag{2}$$

$$W_3 \begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} \frac{1}{4} & 0 \\ 0 & \frac{1}{4} \end{bmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} \frac{3}{8} \\ \frac{1}{4}\sin 60° \end{pmatrix}, \tag{3}$$

$$W_4 \begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} \frac{1}{4}\cos 60° & \frac{1}{4}\sin 60° \\ -\frac{1}{4}\sin 60° & \frac{1}{4}\cos 60° \end{bmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} \frac{5}{8} \\ \frac{1}{4}\sin 60° \end{pmatrix}, \tag{4}$$

$$W_5 \begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} \frac{1}{4} & 0 \\ 0 & \frac{1}{4} \end{bmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} \frac{3}{4} \\ 0 \end{pmatrix}. \tag{5}$$

The generator is then obtained with the union of these five transformations:

$$W(A) = W_1(A) \bigcup W_2(A) \bigcup W_3(A) \bigcup W_4(A) \bigcup W_5(A). \tag{6}$$

C. Geometry of the proposed cauliflower-shaped antenna

The geometrical structure and the dimensions of the designed antenna are presented in Figure 2. The antenna radiator is constructed by a set of successive assemblies of hexagons that create a cauliflower shape. The antenna structure progress during the design stages is shown in Figure 3. The substrate used for the designed antenna is RO-4350B substrate (relative dielectric constant of 3.48 with the loss tangent of 0.0037 and thickness of 1.524 mm). The overall size of the designed antenna is $0.3623\lambda_0 \times 0.41\lambda_0 \times 0.01524\lambda_0$ at 3 GHz as a result of the introduction of a fractal geometry along the edge of the radiating patch and along with the outer corners of the truncated ground plane, an enhanced impedance matching and an extended impedance bandwidth are attained. According to other published works like[1], the resonant frequency f_r of a comparable antenna with a hexagonal patch can be predicted using eqn (7). In addition, the length of each edge constructing the hexagonal patch can be calculated by eqn (8)

$$f_r \approx \frac{U_{mn} c}{2\pi r_e \sqrt{\varepsilon_r}}. \tag{7}$$

The equivalent radius r_e is given by the following formula:

$$r_e = \sqrt{r^2 + \frac{2hr}{\pi \varepsilon_r}\left(\ln\frac{\pi r}{2h} + 1.7726\right)}. \tag{8}$$

The side length of the hexagonal patch can be calculated

Table 1: Parameters of roots for different modes

Mode (n, m)	U_{mn}
0,1	0
1,1	1.84118
2,1	3.05424
0,2	3.83171
3,1	4.20119

using the following formula:

$$q \approx 1.1\, r_e, \tag{9}$$

where ε_r is the dielectric constant of the substrate, c is the speed of light in free space, h is the thickness of the substrate, q is the side length of the hexagonal radiating patch, r is the radius of a comparable circular patch, and U_{mn} is the mth zero of the derivative of the Bessel function of order n. The values of U_{mn} are given as in Table 1.

The dimensions of the designed cauliflower-shaped antenna were optimized to attain the desirable performances.

The physical dimensions of the proposed cauliflower-shaped antenna were set as follows: A = 11.5 mm, d = 0.85 mm, g = 0.25 mm, W_f = 4 mm, W_g = 18.25 mm, and h_g = 9.5 mm.

Figure 4 indicates that the working bandwidth is improved by 17.5% and the impedance matching is highly improved at higher frequencies by inserting the cauliflower-shaped structure along the edge of the hexagonal radiating element and on the outer corners of the truncated ground plane. The working bandwidth of the proposed antenna and the initial designs are given in Table 2.
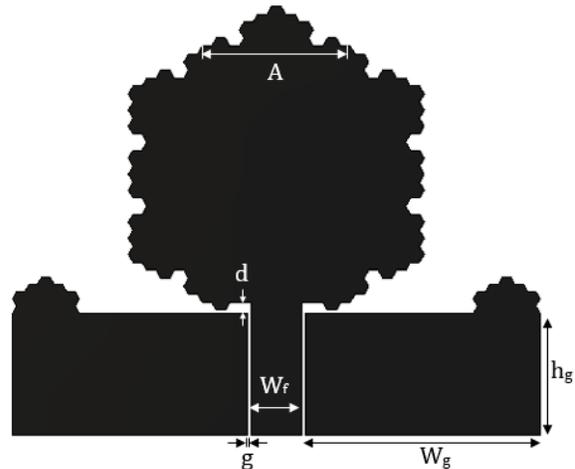
Fig. 2. Detailed configuration of the designed CPW cauliflower-shaped antenna.
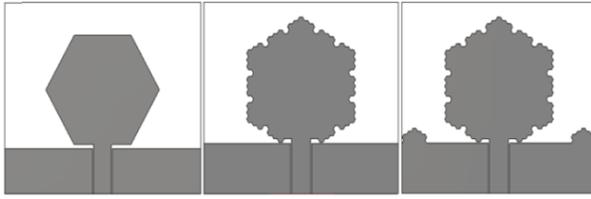
Fig. 3. Antenna geometry development during the design steps. (a) Antenna 1. (b) Antenna 2. (c) Antenna 3.
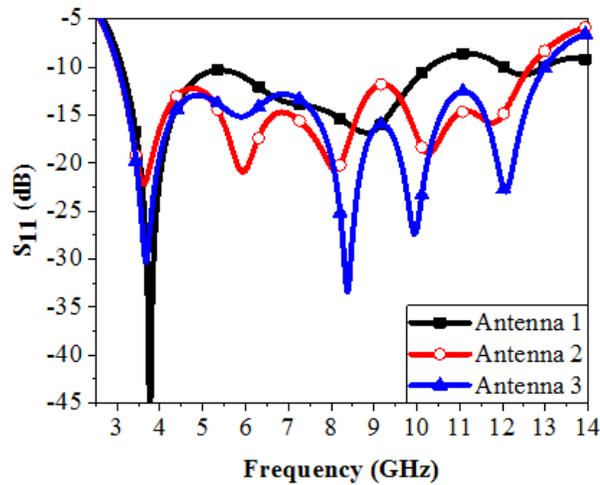
Fig. 4. Influence of the fractal structure on the reflection coefficient of the antenna.

Fig. 5. Real and imaginary parts of the impedance.
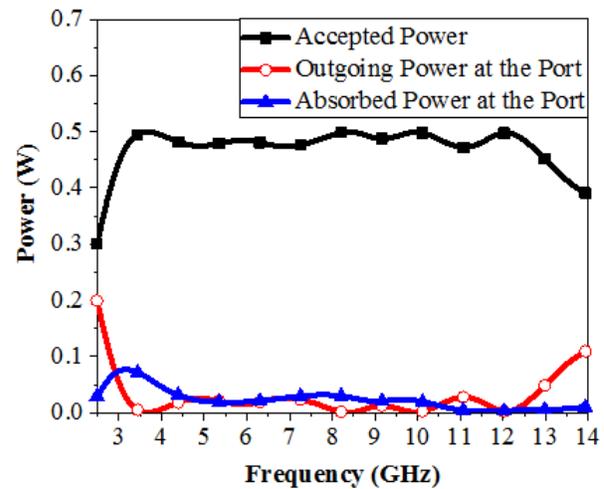
Fig. 6. Powers at the input of the antenna.

Figure 5 indicates that the real part of the impedance is nearer, fluctuating around 50 Ω value which is the input impedance of the excitation port. Whereas, the imaginary part is narrowly fluctuating near zero bar during the working bandwidth. Thus, the designed antenna is well adapted throughout the entire working frequency range. At the input of the antenna, the accepted power is compared with the no-transmitted powers and the obtained results are presented in Figure 6. Compared to the level of the accepted power, negligible powers are recorded which prove the well adaptation of the designed antenna. In order to show the utility of the used fractal geometry, the current distribution on the antenna's surface is presented in Figure 7. At higher frequencies, there is more concentration of the current at the edge of the radiating patch and along the upper edge of the ground plane. The reflections at the edges of the antenna permit creation of other resonant frequencies, which is confirmed by Figure 4. Thus, the fractal geometry has a high contribution to the antenna's performance improvement by engendering additional resonances and allowing to extend the operational bandwidth.

Figure 8 represents a photograph of the fabricated prototype which was printed on the RO-4350B substrate with a total size of $0.3623\lambda_0 \times 0.41\lambda_0 \times 0.01524\lambda_0$ at 3 GHz. To confirm the UWB feature of the designed antenna, the reflection coefficient of the fabricated prototype was measured using an Agilent 8722ES vector network analyzer (VNA) with the specifications given in Table 3. High concordance between the simulation and experimental results is detected and the UWB characteristic of the proposed antenna is validated. Figure 9

Table 2: Antennas working bandwidth comparisons

Antennas	Working band (GHz)	Bandwidth (GHz)	Bandwidth (%)
Antenna 1	3.12-10.30	7.18	107
Antenna 2	3.02-12.64	9.62	122.86
Antenna 3	3.02-12.98	9.96	124.4
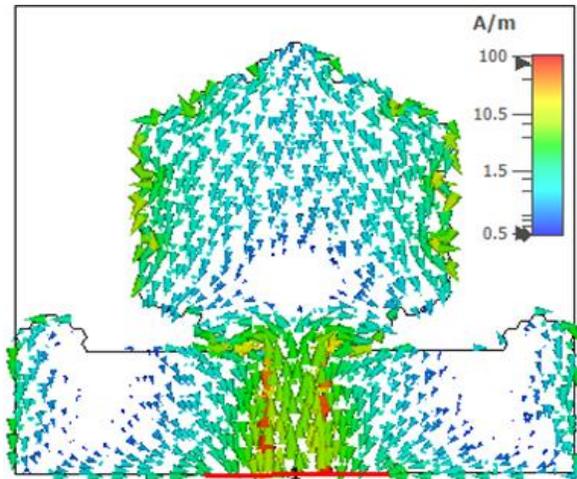
(a)
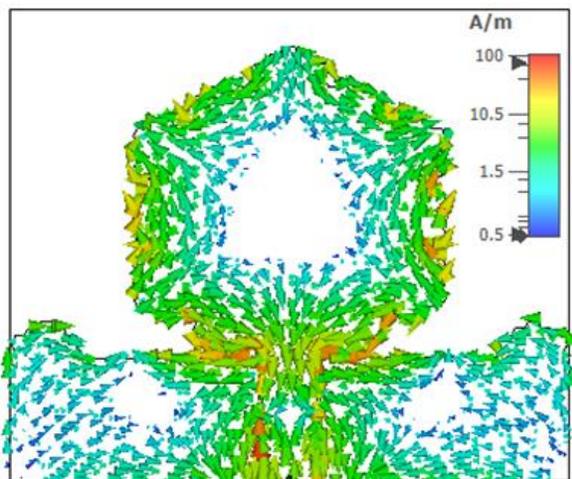
(b)
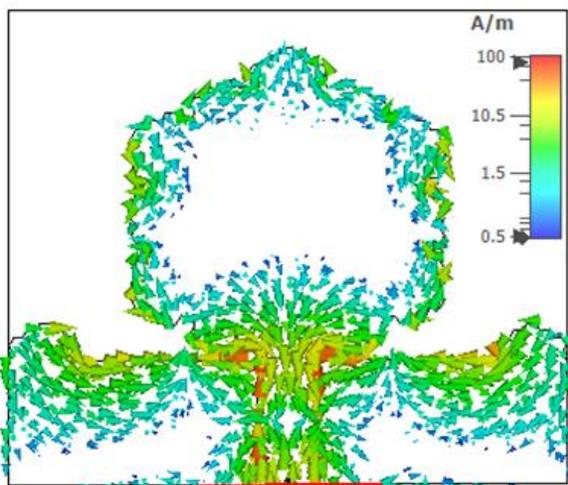
(c)

Fig. 7. Current distribution at three frequencies. (a) 3.65 GHz. (b) 8.37 GHz. (c) 9.89 GHz.
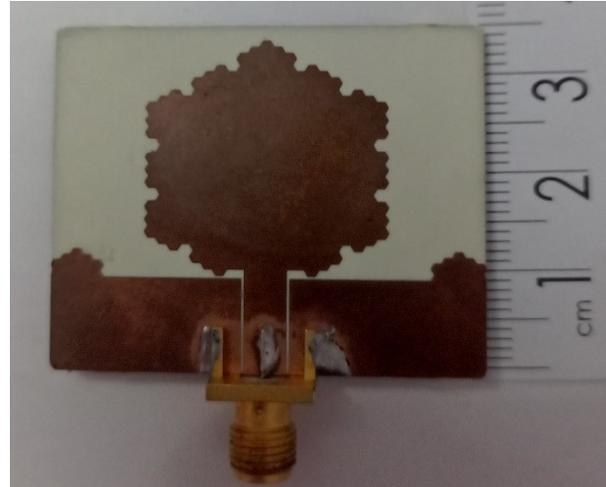
Fig. 8. Fabricated prototype of the proposed UWB CPW cauliflower-shaped antenna.
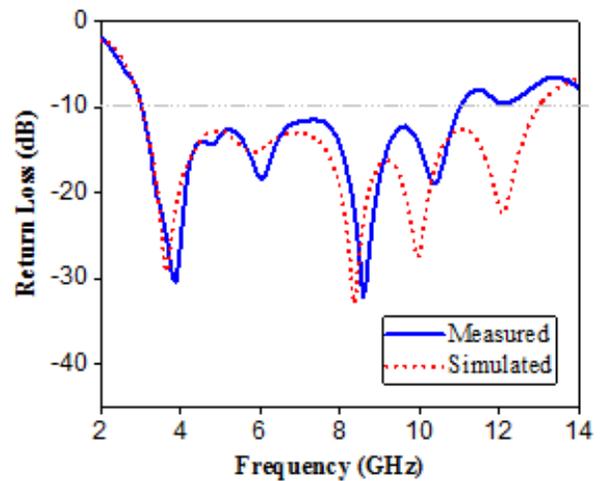
Fig. 9. Measured and simulated reflection coefficient of the proposed UWB CPW cauliflower-shaped antenna.

indicates that the measured reflection coefficient of the fabricated prototype covers a large bandwidth extending from 3.05 to 10.96 GHz (113%), which is wider than the reserved UWB frequency band of 110% (3.1−10.6 GHz).

The experimental co-polar and cross-polar radiation patterns of the fabricated prototype were measured in an anechoic chamber by using two-antenna measurement setup. A double ridged horn antenna (model AH-118 working in the range 1-18 GHz) is used for transmitting electromagnetic waves, whereas the fabricated coplanar waveguide (CPW) cauliflower-shaped antenna is used for receiving them.

The radiation patterns were measured in both the H (xz-plane) and the E (yz-plane) planes at three

Table 3: Specifications of the used VNA

Parameters	Values
Frequency range	0.05−40 GHz
IF bandwidth	10 Hz
Maximum input level	10 dBm
Maximum output power	−5 dBm
Power resolution	0.01 dB
Output power range	70 dB (0.05−20 GHz) 65 dB (20−40 GHz)
Output impedance	50 Ω

(a)

(b)
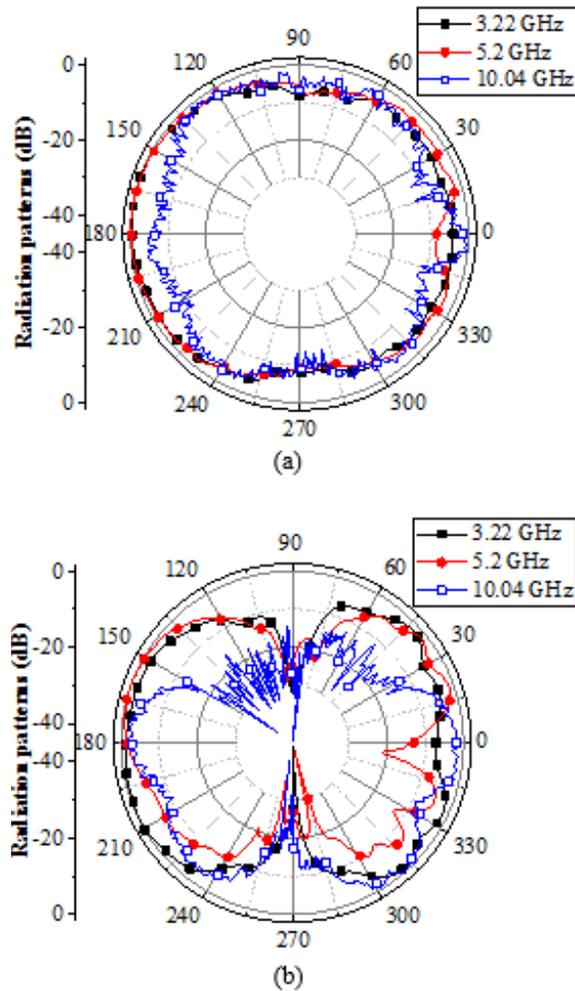
Fig. 10. Measured normalized co-polar radiation patterns at three frequencies from the working bandwidth. (a) xz-plane. (b) yz-plane.

(a)

(b)

Fig. 11. Measured normalized cross-polar radiation patterns at three frequencies from the working bandwidth. (a) xz-plane. (b) yz-plane.

frequencies from the operating bands 3.22, 5.2, and 10.04 GHz. Figure 10 and 11 indicate that the fabricated prototype has nearly consistent omni-directional radiation characteristics in the H-plane and bidirectional radiation patterns, like-dumbbell-shaped ones as a con-ventional monopole, in the E-plane. At higher frequencies, the radiation patterns undergo small distortions due to the reflections along the introduced like-cauliflower-structure and along the upper edge of the ground plane and also due to the excitation of higher-order mode [22].

The cross-polar radiation patterns in the H-plane retain their star shape over the entire working band with low levels compared to those of co-polar radiation patterns, despite the augmentation of their levels with increasing the frequency, which is due to the excitation of hybrid currents [23].

Figure 12 indicates that the gain and the radiation efficiency simulated by the designed antenna throughout the operating frequency are acceptable and rea-

Table 4: Comparison of the fabricated antenna with other recently published antennas

Antennas	Substrates	Sizes (mm^3)	Bandwidths	Ease of fabrication
Ref. [26]	FR4	$100 \times 100 \times 15$ mm^3 $(\lambda_0 \times \lambda_0 \times 0.15\lambda_0)$	2.7−11.8 GHz (125.52%)	Hard
Ref. [27]	FR4	$49 \times 48.5 \times 0.8$ mm^3 $(0.49\lambda_0 \times 0.485\lambda_0 \times 0.008\lambda_0)$	2.9−10.4 GHz (112.78%)	Easy
Ref. [28]	FR4	$169 \times 169 \times 38.46$ mm^3 $(1.69\lambda_0 \times 1.69\lambda_0 \times 0.3846\lambda_0)$	3.8–8.8 GHz (79.36%)	Hard
Ref. [29]	FR4	$50 \times 50 \times 1.6$ mm^3 $(0.5\lambda_0 \times 0.5\lambda_0 \times 0.016\lambda_0)$	1.5–11 GHz (152%)	Easy
Ref. [30]	RO-4003	$100 \times 104 \times 1.5$ mm^3 $(\lambda_0 \times 1.04\lambda_0 \times 0.015\lambda_0)$	2–9 GHz (127.27%)	Hard
Ref. [31]	FR4	$100 \times 100 \times 16$ mm^3 $(\lambda_0 \times \lambda_0 \times 0.16\lambda_0)$	4.7−12.4 GHz (90%)	Hard
Ref. [32]	FR4	$45 \times 40 \times 1.6$ mm^3 $(0.45\lambda_0 \times 0.4\lambda_0 \times 0.016\lambda_0)$	1.31–6.81 GHz (135%)	Hard
Ref. [33]	FR4	$50 \times 50 \times 11.6$ mm^3 $(0.5\lambda_0 \times 0.5\lambda_0 \times 0.116\lambda_0)$	4.3−9.10 GHz (71.64%)	Easy
Ref. [34]	FR4	$40 \times 40 \times 3.2$ mm^3 $(0.4\lambda_0 \times 0.4\lambda_0 \times 0.032\lambda_0)$	5.64–8.63GHz (41.90%)	Easy
Ref. [35]	Taconic RF-35	$120 \times 120 \times 1.6$ mm^3 $(1.2\lambda_0 \times 1.2\lambda_0 \times 0.016\lambda_0)$	1.45–4.86 GHz (108.08%)	Easy
This work	RO-4350B	$36.23 \times 41 \times 1.524$ mm^3 $(0.3623\lambda_0 \times 0.41\lambda_0 \times 0.01524\lambda_0)$	3.05–10.96 GHz (113%)	Easy
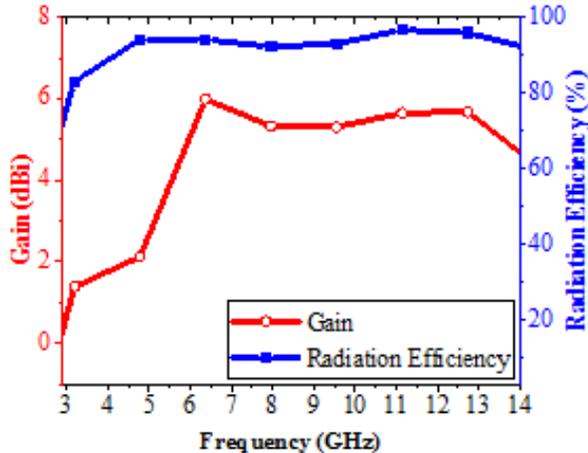
Fig. 12. Gain and radiation efficiency achieved by the designed antenna.

sonable because their values are better than the values obtained by some recently published works. The gain is varying between 1.39 and 5.68 dBi which is better than the one attained in [24]. Whereas, the radiation efficiency is almost over 90% during the working bandwidth which is better than the one achieved in [25].

In Table 4, the main parameters of the proposed antenna are compared with the ones of some recently published printed antennas. It can be deduced that the parameters of the proposed antenna are better or comparable to those of other antennas. With the above mentioned parameters, it could be deduced that the proposed antenna can be very convenient for many UWB systems.

III. CONCLUSION

In this paper, the utility of the fractal concept is investigated for designing a printed CPW-fed cauliflower-shaped antenna for UWB communication applications and systems. The simulation and measurement results have demonstrated that the working bandwidth and the impedance matching have been improved by inserting fractal geometry along the edge of the radiating patch and on the outer corners of the truncated ground plane. A prototype was fabricated and printed in a compact size of $0.3623\lambda_0 \times 0.41\lambda_0 \times 0.01524\lambda_0$ at 3 GHz. The measured results indicated that the cauliflower-shaped fractal antenna is well matched along a large bandwidth extending from 3.05 to 10.96 GHz, which is about 113% enclosing the UWB frequency range. Furthermore, the experimental radiation patterns of the fabricated prototype measured in an anechoic chamber showed stable omni-directional radiation patterns along the operating bandwidth. Besides, reasonable gain (1.39−5.68 dBi) and high radiation efficiency values (>90%) were simulated over the entire operating frequency band. Consequently, the proposed antenna

could be useful for many modern UWB communication systems.

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