INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2019, VOL. 65, NO.2 , PP. 175-180
Manuscript received January 3, 2019; revised April, 2019. DOI: 10.24425/ijet.2019.126298

Compact Coplanar-fed Tree-shaped Antenna

Małgorzata Malinowska, Marek Kitliński

***Abstract*—The paper presents the concept of a fully planar tree-shaped antenna with quasi-fractal geometry. The shape of the proposed radiator is based on a multi-resonant structure. Developed planar tree has symmetrical branches with different length and is fed by a coplanar waveguide (CPW) with modified edge of the ground plane. The antenna of size 29 mm x25 mm has been designed on Taconic - RF-35 substrate (ε_r = 3.5, tgδ_ε= 0.0018, h = 0.762 mm). The paper shows simulated and measured characteristics of return loss, as well as measured radiation patterns. The proposed antenna could be a good candidate for broadband applications (for instance: wideband imaging for medical application and weather monitoring radars in satellite communication etc.)**

***Keywords*—broadband antenna, fractal antenna, reflection coefficient, defected ground structure, coplanar waveguide**

I. Introduction

ANTENNA (radiator) could be called a main component in wireless systems, because based on its performance is easily to estimate and analyze effectiveness of the wireless communication around the world. Radiator is a transducer which task is carrying the current. The antenna, in accordance with the general definition, is used to convert radio frequency (RF) fields into alternating current or vice versa. There are both receiving and transmission antennas for sending or receiving radio transmissions [2]. Therefore, the antennas are very important in wireless systems, because they transmit and receive the information via the air [2,11].

Since the beginning of the 21st century, the design and analysis of antennas and antenna arrays for broadband and Ultra WideBand systems (UWB) are characterized by growing interest. Various applications of electronic systems require designers to pay attention on different properties of antennas, depending on the criterion chosen, for example: size, bandwidth, radiation pattern, gain, efficiency and impedance matching. In world literature, the prevailing proposals include single radiators in a wide range of shapes: from the classic ones (rectangle, triangle, circle) to fractal (curves filling space) and nature shapes (flower, tree); there are also examples of large antenna arrays, but there are definitely fewer ideas [8,9,10].

The microstrip antenna can be a good idea for wideband or UWB system, because it is characterized by the small profile, easy to fabricate and very low cost of fabrication. The microstrip technology consists of two main parts on a dielectric substrate. They are: microstrip transmission line and ground plane which are made of conducting material on one side or on the both sides [7].

The article briefly reviews a couple of different antennas for the broadband applications, constructed over the last decade (2008 - 2018). It is summarized in the form of project of a radiator fed by a coplanar waveguide with modified ground plane.

M. Malinowska and M. Kitliński are with Department of Marine Electronics, Gdynia Maritime University, Gdynia, Poland (e-mail: m.malinowska@wm.umg.edu.pl, m.kitlinski@we.umg.edu.pl).

II. The Literature Review

The table I shows broadband and ultra wideband antennas included in publications from 2008 to 2018. The size of antennas, type of substrate as well as bandwidth were compared. The conclusions and development trends concerning the design of antennas listed below result from the analysis of the publications presented in the table. The following will be used in the next stages of this authors' work:

- Together with the development of antennas, their miniaturization is necessary, dimensions of radiators > 40 mm are rather not useful;
- The shape of resonators using fractal geometry (such as: Koch snowflake, Sierpinski triangle, Peano curve) [12, 14] or nature geometry (sunflower, tree) are often used in the radiator designs;
- Antenna designers, in order to broaden the bandwidth, change shape of the coplanar feed line [12], as well as they use of modifications in the ground plane (called Defected Ground Structure, DGS);
- Nowadays, for UWB antennas it is crucial to occupy extremely wide bandwidth, but on the other hand, designers try to reject the selected bands to avoid interference with other systems, for example: 5.15 - 5.825 [GHz];
- Interesting trend is observed in the matter of substrate. Although still the most popular is FR4 substrate (the cheapest one), 1.5 -1.6 mm thick or more. Nevertheless, it is possible in last publications [17] one can find very thin new flexible laminates 118 µm.

III. Fractal Antenna

The modern and interesting approach which can be used with in wireless communication is fractal geometries to design compact multiband (or wideband) printed antennas. *"Fractal geometry is a family of geometries that have the characteristics of inherent self-similar or self-affinity, which were used to describe and model complex shapes found in nature such as mountain ranges, waves and trees*" [5].

Currently, fractal geometries are very widely applied in different scientific and technological disciplines, for example: in fluid mechanics, computer science, astronomy, medicine etc. As it was mentioned before, in antenna design also applies fractal shapes (in 1988 dr. Nathan Cohen built the world's first fractal element antenna) and this technique named "*fractal antenna engineering*".

There are advantages of using fractal geometries [14,23, 24]:

- it is possible to reduce the size of the radiator, which makes it a good candidate for antenna miniaturization;
- the fractal structures are self-filling that might be scaled without increasing the overall size, it is very useful for small antenna;
- the fractal are self-repeated at different scales, it can provide a wideband or multiband operating of antenna;
- antennas with fractal shape give a better input impedance occurred in comparison of other antennas;
- the fractal structures give the possibility to add inductance and/or capacitance without using any component;
- the fractal structure can increase the electrical path length.

However, not all the known fractal geometries can form the antenna design. For instance, two popular curves: Hilbert and Peano, cannot effectively reduce the resonant frequency of the antenna due to the exhibiting a high degree of space filling which cause the cancelling of the current between closely spaced lines [24].

Fortunately, previous research has shown that a fractal tree-shaped radiator may be a good solution for design of antennas [14].

IV. DEFECTED GROUND STRUCTURE

The Defected Ground Structure (abbreviated as DGS) is one of the solutions for radiator design. DGS is applied mainly to improve the impedance bandwidth of the microstrip antenna [22]. It is an etched periodic or non-periodic cascaded configuration defect in ground of a planar transmission line (coplanar, microstrip and conductor backed coplanar wave guide) [3]. The defect may have a simple or very complicated shape. Modified ground structure is applied in order to [22]:

- increase the input impedance bandwidth;
- reduce the size of an antenna;
- achieve a lower resonance frequency;
- improve other parameters in the antennas (especially performance).

TABLE I
THE SELECTED REPORTED BROADBANDANTENNAS IN THE YEARS 2008 - 2018

Dimensions [mm^2]	Size in λ	Bandwidth [GHz]	Substrate(relative permittivity)	References	Year of publication
20x30	0.3λx0.45λ	2.8-6.2	FR4 ε_r=4.4	Design of the tree-shaped UWB antenna using fractal concept [6]	2008
80x90x1.53	0.726λx0.817λ x0.014λ	0.95 – 4.495	FR4 ε_r=4.3	On the design of wheel shaped fractal antenna [20]	2011
52.45x58x1.53	1.53λx1.692λ x0.045λ	2.5 - 15	FR4 ε_r=4.3	On the design of inscribed pentagonal-cut fractal antenna for ultra wideband application's [19]	2011
20x25	0.55λx0.688λ	1 -15	FR4 ε_r=4.3	Miniaturized UWB monopole microstrip antenna design by the combination of Giusepe Peano and Sierpinski carpet fractals [5]	2011
32x33x1.59	0.8λx0.825λx0.04λ	3 – 12 without 5.15 – 5.825	FR4 ε_r=4.4	Hexagonal boundary Sierpinski carpet fractal shaped compact ultra wideband antenna with band rejection functionality [18]	2013
14x18x1	0.368λx0.473λ x0.026λ	2.95 -12.81	FR4 ε_r=4.4	Very compact UWB CPW-fed fractal antenna using modified ground plane and unit cells [13]	2014
50x50x1.6	1.147λx1.147λ x0.037λ	3.52 -10.24	FR4 ε_r=4.7	Analysis of fractal antenna for ultra wideband application [15]	2014
14x18x1.6	0.368λx0.473λ x0.042λ	2.95 – 12.81	FR4 ε_r=4.4	Ultra-wideband tapered patch antenna with fractal slots for dual notch application [4]	2014
20x25x1.5	0.506λx0.633λ x0.038λ	3.1 – 12.08	FR4 ε_r=4.3	Modified ground plane of patch antenna for broadband applications in C-band [16]	2016
30x22x1.6	1.035λx0.759λ x0.055λ	3.2-17.5	FR4 ε_r=4.6	Design of compact UWB monopole planar antenna with modified partial ground plane [21]	2018
40x22x0.1	1.007λx0.554λ x0.04λ	4.5 – 10.6	LCP ε_r=2.9	Time domain analysis for foldable thin UWB monopole antenna [17]	2018

V. ANTENNA DESIGN

The concept of antenna in the shape of a quasi-fractal tree is presented. The proposed shape of the radiator is a typical multi-resonance structure, also called quasi-periodic structure. The antenna has symmetrical branches of different lengths. It is fabricated on the Taconic - RF-35, with an overall dimension of 29 mm x 25 mm, the dielectric material has the below described features:

- metallic thickness: t =18μm;
- substrate thickness: h = 0.762 mm;
- relative dielectric permittivity ε_r = 3.5;
- dielectric loss: tan(δ)=0.0018.

The geometry details of the proposed antenna are (the detailed geometry of the design structure is shown in Fig. 1):

- height of the tree - 29 mm;
- length of the branches are: 11.5 mm, 2.5 mm, 9 mm, 2.5 mm, 7 mm and the last 5 mm.

A coplanar waveguide (CPW) was used to feed antenna, which gives better impedance matching, especially in a wide range of frequencies. The dimensions of the coplanar wave guide are:

- the central strip width - 2 mm;
- the width of the slots - 0.3 mm;
- and total length of the line - 6.5 mm.

In order to improve the impedance matching characteristics in the operating frequency band, the ground plane with modification is adopted. The modified ground plane has two symmetrically rectangular cuts: on the corners (dimensions of 1.3 mm x 1.5 mm) and a close radiator (dimensions of 0.4 mm x 4.5 mm).

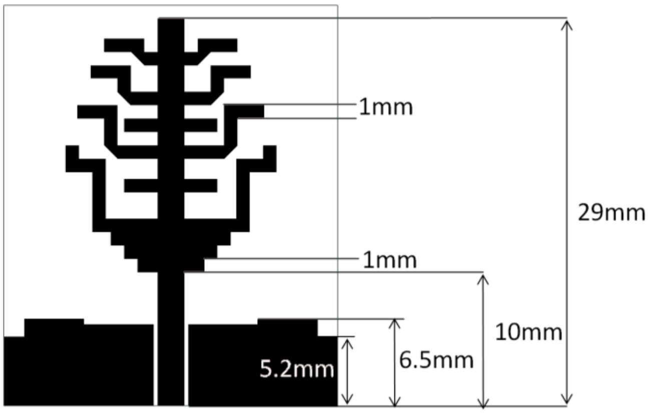

Fig. 1. The geometry of the proposed antenna.

The final design is using two different computer simulators in order to achieve a bandwidth as high as possible:

- Computer Simulation of Momentum 3D Planar EM Simulator, which is a tool of the ADS program (Advanced Design Systems, ADS 2016, company Keysight Technologies [27]);
- Computer Simulation Technology CST Microwave Studio Suite 2014 (CST 2014, company Computer Simulation Technology [28]).

It should be noted that the antenna operating band has been defined (in accordance with the general rule) as the frequency range at which the return loss S_{11} is lower than -10 dB. It means that at least 90% of input power is delivered to device and reflected power is lower than 10%.

VI. EFFECT OF MODIFITED GROUND PALNE

The characteristics of the reflection coefficient (S_{11}) for the proposed shape of the antenna with modified ground plane was compared with CPW-fed radiator without modified ground plane. The geometry of simulated antennas is presented on Fig. 2. The results of simulations in ADS are shown in Fig. 3.

It is observed that (graph on Fig. 3) the modified of ground plane structure limits the reflections at the input of antenna. It has been found that such solution improves the impedance matching in the central and higher frequencies of the frequency range (especially 11.2 GHz -12.2 GHz). As a consequence, a broad spectrum of antenna frequency was obtained, i.e. 7.4 to 12.7 GHz (for antenna without modified ground, it achieves the double band from 7.8 to 11.2 GHz and from 12.2 to 12.5 GHz).

VII. THE EFFECT OF TREE SHAPE

The effect of the tree shape on the reflection coefficient of antenna was checked. The proposed geometry can be called quasi-fractal, because of the branches have the features of self-similar.

The three different tree shapes were compared (see figure 4). The all of proposed antennas have 29 mm height. The first radiator (antenna 1) has six straight branches with different length. Antenna with number 2 has four curved and two straight branches. The third antenna, it is final project, its exact dimensions are shown in Figure 1. It is worth mentioning, that the important modification is the introduction of three stairs between trunk and crown of tree.

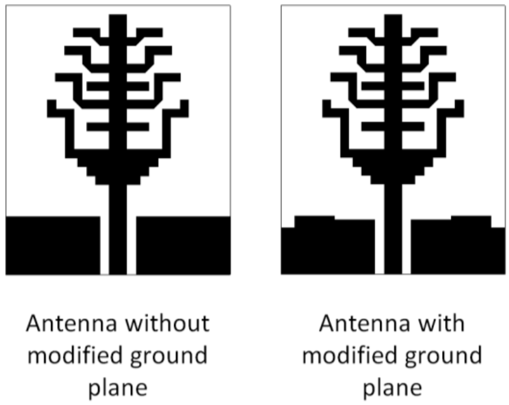

Fig.2. The geometry of the proposed antennas with and without modified ground plane.

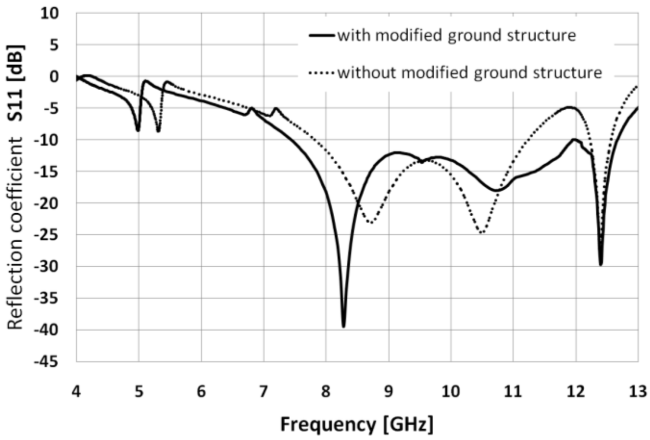

Fig. 3. Comparison of reflection coefficient characteristics for the proposed shape of the antenna with modified ground plane and antenna without modified ground structure (Momentum ADS 2016) [27].

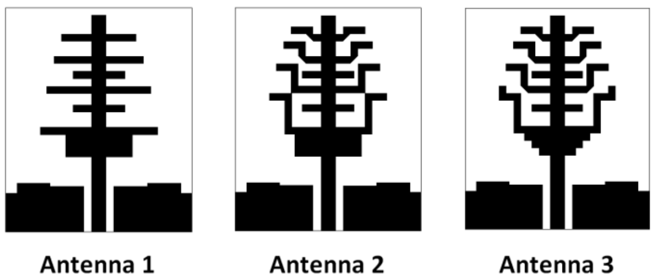

Fig. 4. The geometry of three different tree antennas.

The graph in Figure 5 shows three curves of return loss (reflection coefficient, S_{11}) depending on frequency. The antenna 1 (with all straight branches) has a single operating band in the range 6.79 - 6.89 GHz. The second proposal of radiator with four curved branches allows to achieve a three different bandwidth: 7.41 - 8.35 GHz, then 10.26 - 11.40 GHz and the last 12.23 - 12.83 GHz. The final proposal of antenna (antenna 3) operates from 7.4 GHz to 12.7 GHz. This effect has been obtained by curved branches and three steps between trunk and crown of tree, which cause to increase the electrical path length.

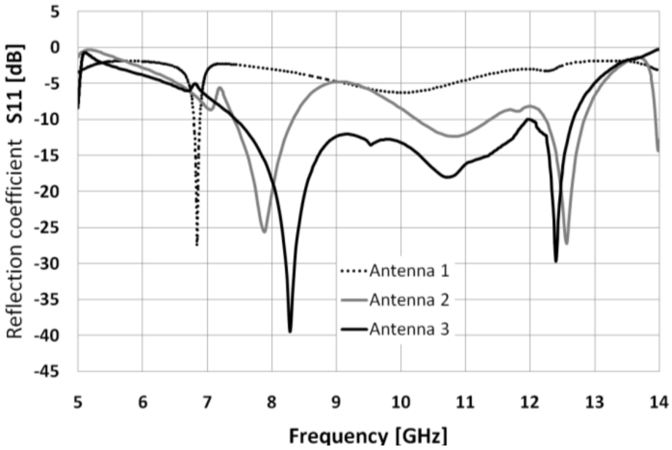

Fig. 5. Comparison of reflection coefficient characteristics for the three different shape of the antennas (Momentum ADS 2016) [27].

VIII. ANTENNA FABRICATION AND MEASURMENTS

The fabricated prototype is shown in Fig. 6. The experimental measurement of reflection coefficient (S_{11}) for the designed prototype was performed and the comparison between simulated (used two different simulators) and experimental results is shown in Fig. 7.

Fig. 6. Fabricated prototype of the planar tree UWB antenna.

The experiments confirmed the possibility of wideband antenna operation, however, the characteristic of S_{11} (reflection coefficient) has changed slightly in relation to simulation results in ADS. As a result of measurements obtained two operating bands, first a narrow band from 6.45 to 6.55 GHz and second wide band from 7.95 to 13.3 GHz. It may be noted that measurements and ADS simulations, have a good impedance matching for two frequencies 8.3 GHz and 12.3 GHz. The measurements gave the same bandwidth i.e. 5.3 GHz, but the operation band is slightly shifted down from the one predicted in the project ADS (7.4 - 12.7 GHz) to (7.95 - 13.3 GHz) obtained in the measurements. In conclusion, this antenna works very well in X-band (8 - 12 GHz).

On the basis of the results on Fig. 7, the usefulness of the different methods of antenna computer simulators (ADS and CST) can also be assessed. "*For the CST, its tool is based on the FDTD (the finite-difference time domain) method, based on the gridding the spatial and time with same way for the electric and magnetic fields by aligning the E cell with the boundary of the configuration. While the technique behind ADS is the method of moment which is based on the formulating of the unknown current on the radiating patch, the microstrip transmission line and their image on the ground plane by an integral equation*" [1].

In the case of discussed antenna the better convergence of results of simulation and measurements is achieved using Momentum ADS 2016 while designing with CST 2014 allows to observe (additionally) a three different operating ranges: 5.07 - 5.20 GHz, then 8.63 - 10.46 GHz and the last 11.75 -12.61 GHz.

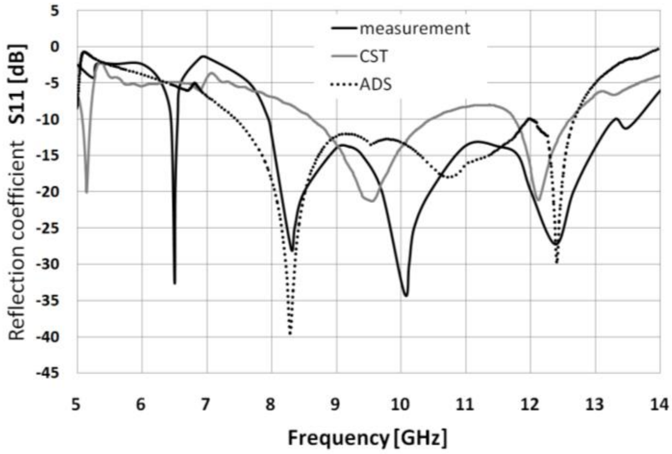

Fig. 7.Measured [26] and simulated reflection coefficient of the proposed antenna (Momentum ADS 2016 and CST Microwave Studio 2014).

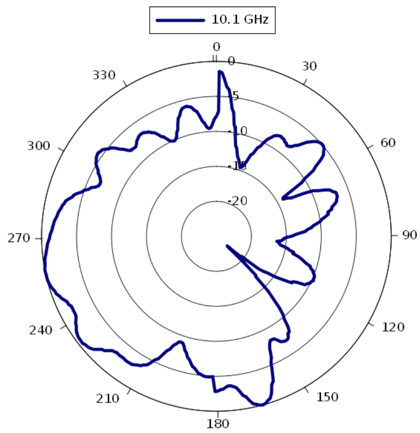

Fig.8. Radiation patterns [dB] for f = 10.1GHz for elevation plane [26].

The bandwidth of the radiator shown in comparison to the results known from literature (Table I) is lower. It is a result of the thickness of the substrate chosen, which has a significant influence on the width of the operating frequency band. It is worth to underline the thickness of the used laminate (0.762 mm) is nearly half the size of the popular ones (1.5 - 1.6 mm). Thicker substrate makes it easier to obtain a wide band.

As part of the research, radiation patterns were determined for two frequencies: 10.1 GHz (Fig.8 and Fig.9) and 12.3 GHz (Fig.10 and Fig.11). The antenna radiates in all directions, there are side lobes that may interfere with the correct (almost omnidirectional) operation of the radiator.

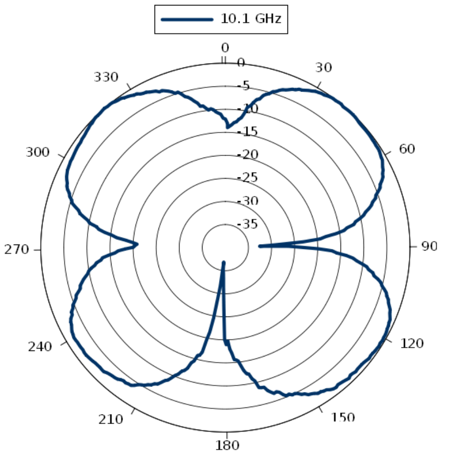

Fig. 9. Radiation patterns [dB] for f = 10.1GHz for azimuth plane [26].

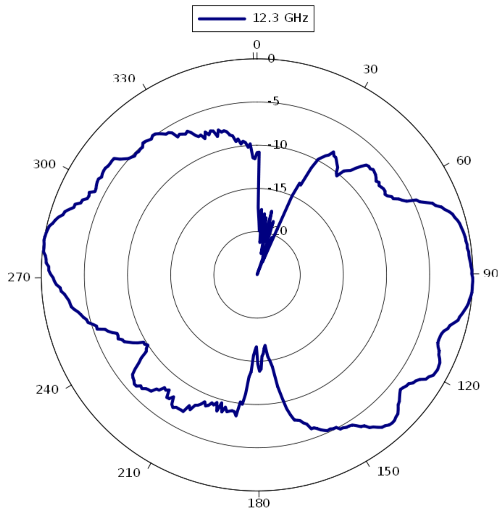

Fig. 10. Radiation patterns [dB] for f = 12.3 GHz for elevation plane [26].

The radiation pattern in the frequency 10.1 GHz in the elevation plane (Fig. 8) shows the appearance of side lobes so that the radiation level of the antenna is not the same, but generally the antenna radiates in all directions. For the second selected frequency, i.e. 12.3 GHz, similar observations are recorded, except that the radiation pattern in the elevation plane is more symmetrical (Fig. 10). In the azimuth plane (Fig. 9 and Fig.11) the characteristics of the antenna operation show omnidirectional properties, however, along with the increase in frequency, further additional side lobes appear.

The simulation results also suggest that the antenna has moderate gain and efficiency at its operation frequency bands. Table II summarizes the peak gain and radiation efficiency at the desired frequencies. It is observed that at 10.5-12 GHz, the radiation efficiency is rather low (63–67 %) compared to other resonant frequencies.

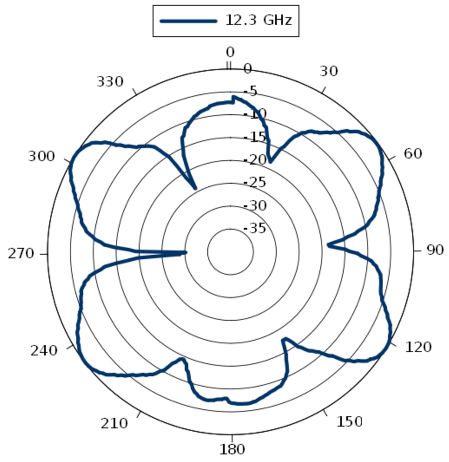

Fig. 11. Radiation patterns [dB] for f = 12.3 GHz for azimuth plane [26].

TABLE II
SIMULATED PEAK GAIN AND RADIATION EFFICIENCY OF THE PROPOSED ANTENNA AT CHOSEN FREQUENCIES

Frequency [GHz]	Simulated Peak Gain [dBi]	Radiation Efficiency [%]
7.5	2.2	73.6
8	2.73	75.61
8.5	2.98	77.22
9	3.4	79.16
9.5	4.16	75.3
10	4.93	72.78
10.5	4.41	67.1
11	4.43	66.33
11.5	3.62	66.1
12	4.13	63.29
12.3	5.53	73
12.5	5.7	82.1
13	5.4	98

In order to expressed “the compactness” of wideband antennas, the authors used index term named as bandwidth dimension ratio (BDR) [25]. This index term indicates how much operating bandwidth can be provided per unit electrical parameter. The BDR equation is written as follows:

$$\mathrm{BDR} = \frac{(\mathrm{BW\%})}{(\lambda_{\mathrm{length}} * \lambda_{\mathrm{width}} * \lambda_{\mathrm{height}})} \quad (1)$$

TABLE III
COMPARISON OF THE PROPOSED ANTENNA WITH SELECTED REPORTED ANTENNAS

References	Size (mm^3)	BDR	Operating frequency [GHz]
[20]	80x90x1.53	11820.19	0.95 – 4.495
[19]	52.45x58x1.53	30692.84	2.5 - 15
[18]	32x33x1.59	71469.41	3 – 12
[15]	50x50x1.6	24418.6	3.52-10.24
[4]	14x18x1.6	310334.6	2.95 – 12.81
[16]	20x25x1.5	157751.4	3.1 – 12.08
[21]	30x22x1.6	130837.4	3.2-17.5
[17]	40x22x0.1	57382.6	4.5 – 10.6
Proposed	25x29x0.762	91144.79	7.95 – 13.3

The results of bandwidth dimension ratio for nine different antennas are shown in Table III. The proposed antenna has achieved the BDR value of 91144. It is not the best, but good result, despite the relatively narrow operating frequency (in comparison to UWB antennas). Therefore, it can be concluded that proposed shape of quasi-fractal tree might be a good and promising perspective for single or multiple radiator antenna.

IX. CONCLUSION

A novel planar tree antenna for broadband operation is designed having a dimension of 29 x 25 mm^2(size in λ; 1.027λ x 0.885λ x 0.027λ). The introduced modifications of the proposed antenna concern quasi-fractal shape, coplanar waveguide in feeding system, relatively thin substrate and modified defected ground structure. It is observed from electromagnetic simulation that the proposed antenna has attained -10 dB impedance bandwidth of 5.3 GHz (7.4–12.7 GHz). The measurements show that real radiator operates from 7.4 GHz to 12.7 GHz (impedance bandwidth of 5.35 GHz). This effect has been obtained by curved branches and three steps between trunk and crown of tree, which allow to increase the electrical path length. Based on calculated index term BDR, it can be concluded that proposed shape of quasi-fractal tree might be a good perspective for single or multi radiator antennas.

The quasi-fractal shape of radiator and modified edge of the ground plane used in the proposed antenna show that slight modifications introduced can lead to design of an attractive broadband antenna. The presented antenna is a good candidate for X-band (8 - 12 GHz) applications, for instance: in ultra wideband imaging (medical applications), weather monitoring radars or different satellite communication systems.

REFERENCES

[1] A. El. Hamdouni, A. Tajmouati, J. Zbitou, A. Errkik, L. El Abdellaoui, M. Latrach, “A New Design of an UWB Circular Fractal Printed Antenna” Telkomnika, Vol.16, No.5, pp. 1931-1938, 2018.

[2] Balanis C.A., “ Antenna Theory, Third edition”, John Wiley & Sons, Inc., New York 2005.

[3] Dhanashri S. Salgare, Shamala R. Mahadik, "A Review of Defected Ground Structure for Microstrip Antennas", *IRJET*, vol. 2, no. 6, pp. 150 - 154, 2015.

[4] F.B. Zarrabi, A.M. Shire,M. Rahimi, N.P. Gandji, “Ultra-wideband tapered patch antenna with fractal slots for dual notch application” , Microwave Opt TechnolLett 56, pp. 1344–1348, 2014.

[5] H. Oraizi, S. Hedayati, “Miniaturized UWB monopole microstrip antenna design by the combination of GiusepePeano and Sierpinski carpet fractals”, IEEE Antennas Wireless Propag Lett 10, pp. 67–70, 2011.

[6] J.K. Park, H.S. An, J.N. Lee, “Design of the tree-shaped UWB antenna using fractal concept”, Microwave Opt TechnolLett50, pp. 144–150, 2008.

[7] K. P. Ray, “Design Aspects of Printed Monopole Antennas for Ultra-Wide Band Applications,” International Journal of Antennas and Propagation, vol. 2008, Article ID 713858, 2008.

[8] K. Rudyk, R. Kubacki, S. Lamari, “Antena ultra-szerokopasmowa ze strukturą periodyczną” Przegląd Elektrotechniczny, R. 92 nr 12/2016, pp. 149 -152, 2016.

[9] L. Yang and G. B. Giannakis, “Ultra-wideband communications - an idea whose time has come”, IEEE Signal Processing Magazine, vol. 21, pp. 26–54, 2004.

[10] M. Garbaruk „ Konstrukcje i charakterystyki czteroelementowej anteny ultraszerokopasmowej UWB” Przegląd Elektrotechniczny, R. 90 nr 12/2014 pp.64 -67, 2014.

[11] M.Gunavathi, P.Ramya, P.Hamsagayathri, D.Kavitha, “Design and simulation of miniaturized UWB microstrip patch antenna for wireless communication” , International Research Journal of Engineering and Technology, Volume 03, Issue 04, pp 1-6, 2016.

[12] M. Kitlinski, R. Kieda, “Compact CPW-fed Sierpinski fractalmonopole antenna”, Electronics Letters, Vol. 40 No. 22,pp.1387-1388, 2004.

[13] M. Jalali, T. Sedghi, “Very compact UWB CPW-fed fractal antenna using modified ground plane and unit cells”, Microwave Opt TechnolLett 56, pp. 851–854, 2014.

[14] M. Malinowska, “Antena fraktalna – badanie wpływu stopnia iteracji drzewa fraktalnego na częstotliwości rezonansowe oraz dobroć anten”, Zeszyty Naukowe Akademii Morskiej w Gdyni, nr 95 pp. 54 -65, 2016.

[15] N.M. Sahar, M.T. Islamand N. Misran, “Analysis of fractal antenna for ultra wideband application”, Res J ApplSciEngTechnol **7**, pp. 2022–2026, 2014.

[16] P. JyotiGogoi, D. JyotiGogoi, S.N. Bhattacharyya, “Modified ground plane of patch antenna for broadband applications in C-band”, Microw Opt TechnolLett 58(5), pp. 1074–1078, 2016.

[17] R.Sherif Zahran, AbdelhamidGaafar, A. Mahmoud Abdalla “Time domain analysis for foldable thin UWB monopole antenna” AEU - International Journal of Electronics and Communications, Volume 83, pp. 253 -262, 2018.

[18] R. Ghatak, A. Karmakar, D.R. Poddar, “Hexagonal boundary Sierpinski carpet fractal shaped compact ultra wideband antenna with band rejection functionality”, AEU Int J Electron Commun 67, pp. 250–255, 2013.

[19] R. Kumar, P.N. Chaubey, “On the design of inscribed pentagonal-cut fractal antenna for ultra wideband applications”, Microwave Opt TechnolLett 53, pp. 2828–2830, 2011.

[20] R. Kumar, P. Malathi, K. Sawant, “On the design of wheel shaped fractal antenna”, Microwave Opt TechnolLett 53, pp. 155–158, 2011.

[21] SwarnapravaSahoo, Laxmi Prasad Mishra, Mihir Narayan Mohanty, Rabindra Kishore Mishra “Design of compact UWB monopole planar antenna with modified partial ground plane” Microw Opt TechnolLett , Volume 60, Issue 3, pp. 578 -583, 2018.

[22] S. Elajoumi, A. Tajmouati, M. C. Abounaima, A. Errkik, L. Elabdellaoui, M. Latrach, “Compact Ultra-Wideband Printed Monopole Microstrip Antenna with Defected Ground Structure” International conference on computing and wireless communication systems, pp. 5 – 10, 2016.

[23] Shruti R.S Parmar, Er. Hardeep Singh ” Analysis of Fractal Geometries and its Applications in Microstrip Antenna”,International Journal of Advanced Research in Computer Science, Volumne 8, No.4, pp.194 – 198, 2017.

[24] Qi. Luo, J. Rocha Pereira, H. Salgado „Low Cost Compact Multiband Printed Monopole Antennas and Arrays for Wireless Communications” Progress in Compact Antennas – Chapter -3,pp. 87 - 84, 2014.

[25] M. Mahmud, T. Alam, and M. Islam. “A triangular coupled-resonator antenna for ultra-wideband applications” Applied Physics A: Materials Science and Processing, 123(1):2–5, 2017.

[26] P. Jermakowicz, „Ultraszerokopasmowe anteny planarne dla systemów komunikacji bezprzewodowej”, praca dyplomowa magisterska, Politechnika Gdańska, 2009.

[27] Advanced Design System (ADS 2016)www.keysight.com.

[28] CST Microwave Studio (CST 2014) www.cst.com;