Fractal Antennas for Super Wideband Applications

Luka Lazović, Branka Jokanovic, Vesna Rubežić and Ana Jovanović

Abstract—**This paper presents the design of original super-wideband printed fractal antennas that can be used in energy harvesting and IoT applications. The proposed fractal antennas are based on shape of a cardioid. A review and recent developments of fractal antennas are also presented in order to compare obtained results. Taking into account the expansion of information and communication technologies as well as prediction of an enormous increase in the number of devices that will use wireless communications, moreover the Energy Harvesting concept and the IoT concept, it is clear that it is challenging to design an antenna to cover all the bands with a high surface density of electromagnetic radiation and an antenna that covers all the necessary communication bands. Based on the described requirements, designed antennas should meet the following criteria: ultra-broadband, electrically small antennas, planar and easy to manufacture, made on an inexpensive substrate, robust against material inhomogeneity and manufacturing errors.**

The first proposed antenna is a uniplanar ultra-wideband fractal slot antenna that operates in the range of 1.8 GHz to 30 GHz and has extremely small electrical dimensions of only 0.21λ×0.285λ at the lowest frequency of 1.8 GHz. The second proposed antennas are ultra-wideband fractal monopole antennas operating in the 4 GHz to 30 GHz range. The antenna is electrically small, measuring 0.33λ × 0.25λ. Experimental verification confirmed the results obtained through simulations, while comparison with the literature established the advantages of the proposed antennas.

Index Terms— **Fractal antennas, Ultra-wideband antennas, Microwave antennas, Printed antennas, Monopol antennas, Energy Harvesting, Fractals.**

I. Introduction

TAKING into account the expansion of information and communication technologies, especially mobile communications, and bearing in mind the prediction that in a few years 38 billion devices will be connected within the IoT concept and 1.5 billion on the 5G network, it is clear that the development of technology must go towards simple and cheap solutions. Given that all devices are wirelessly connected, as well as the fact that the next generations of mobile communications use spatial filtering, antennas become key elements to work on in terms of simplification. On the other hand, the very expansion of wireless communications, of any type, leads to an increase in radiated electromagnetic energy, which is why the Energy Harvesting concept, which collects ambient electromagnetic energy, is gaining popularity. Of course, now more than ever it is desirable for devices within the IoT concept to have an autonomous power supply using an antenna, because they are designed to work with very low power consumption, and at the same time to use the same antenna for all the communications they need. This means that it is necessary to design such an antenna that can be used for the Energy Harvesting concept, i.e. to cover all the bands in which there is a high density of electromagnetic radiation and an antenna that covers all the necessary communication bands. In other words, an ultra-broadband or frequency-independent antenna should be designed, which has an omnidirectional radiation pattern and good efficiency. In addition to all of the above, the key thing is that the antenna should be of small dimensions, i.e., to be an electrically small antenna, on a very cheap substrate with a planar geometry that can be very easy made on the same substrate as the rest of the electronics in the device. Taking into account the price of the sensor and materials and the simplicity of manufacturing, the antenna should be robust against manufacturing errors and in case of poor-quality materials.

A large number of antennas with different performances and for use in various systems can be found in the literature. In order for the antenna to be usable, it should efficiently radiate electromagnetic waves with as high directivity and gain as possible, or it should have omnidirectional radiation and high gain. On the other hand, there is also the requirement that the antenna be electrically small. It is also desirable that it has as large a working range as possible, i.e., to be broadband. These goals are in conflict with physical limitations, which is especially evident at high frequencies. Essentially, any antenna is a compromise between these requirements. A particularly interesting group are fractal antennas. The shape of these antennas is based on fractal geometry. Generally speaking, these antennas are naturally broadband and electrically small antennas, and they prove to be very efficient, especially in combination with other types of antennas. It is clear that many good solutions can be found in the literature, but most often it is about antennas of large dimensions (which are not planar) and antennas on extremely expensive substrates where the price of the antenna greatly exceeds the price of the device itself.

5G communication systems also require a simple multi-

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frequency broadband antenna to cover all commercial bands [1]. One of the key techniques introduced in the fifth generation is spatial multiplexing or spatial filtering. Antenna arrays on both the transmitting and receiving side are the foundation of this technology.

The idea for the geometry of these proposed antennas is the Mandelbrot fractal, that is, the cardioid as the basic geometry of that fractal [2]. Analyzing various fractal geometries in which the cardioid is the basic shape with the idea of designing a multiresonant antenna that covers as many commercial bands as possible, a fractal geometry and antenna type with optimal parameters were designed where these antennas meet all the above criteria and are ultra - broadband. These antennas are made on a very cheap and widely available FR-4 substrate.

II. Fractals and Fractal Antennas

A fractal is an irregular geometric structure, i.e. a pattern that repeats ad infinitum and each part of the fractal, which is progressively smaller than the last, looks very similar to the whole structure. Fractals cannot be described by classical geometry because enlarging the structure reveals repeated patterns of similar but progressively smaller dimensions [3], [4].

Fig. 1 Fractals in nature. In order: snowflake, section of cabbage head, bismuth crystals, flower, aloe plant, fern, river basin, snail shell, desert river and leaf.

Most fractals can be constructed using iterative procedure called IFS (Iterated Function Systems). IFS is based on affine transformations that are applied to a certain shape in multiple iterations. These affine transformations consist of translations, scaling, distortions, and rotations. Fractal geometry, especially in the case of its use for designing antennas, can be described using two parameters: the iteration factor - IF and the iteration order - IO. This approach is much simpler and more practical for describing fractal geometry [5], because the fractal dimension cannot be of much use to us when describing fractals. The iteration order IO represents the number of iterations of the fractal, while the iteration factor IF represents the ratio of the dimensions of the second and first iteration of the fractal. In the case of the cardioids presented in this paper, the IF is always less than one because the dimension of the fractal in some iteration is always smaller compared to the dimension of the fractal in the previous iteration. The iteration factor would be defined as:

$$IF = \frac{a_2}{a_1} \tag{1}$$

In general, most fractals and fractal antennas have the same IF for each iteration. In the case of the design of multi-resonant antennas, this would mean, in most cases, that the antennas have harmonic resonant frequencies. On the other hand, it is often necessary to design an antenna that has non-harmonic resonant frequencies.

In this paper, an antenna based on fractal geometry is proposed, where the *IF* changes with each subsequent iteration. This would mean that IF_0 should be defined, which represents the relationship between a_2 and a_1, then IF_1, which represents the relationship between a_3 and a_2 etc. Such fractal geometry allows additional flexibility in designing antennas. Such fractals are said to have multi-fractal scaling.

The cardioid curve is the basis of the fractal geometry of the proposed antennas. A cardioid is a curved line in a plane described by a point on a circle that rolls around a fixed circle of the same radius. The parametric expression for drawing the cardioid is:

$$\begin{aligned} x &= 2a\cos\theta(1-\cos\theta) \\ y &= 2a\sin\theta(1-\cos\theta) \end{aligned} \tag{2}$$

The parameter a in the equation 2 also determines the dimensions of the cardioid and can be used as a parameter that scales the cardioid in relation to the coordinate origin. The dimensions of the cardioid, along the x-axis are from -4 to 0.5, and along the y-axis from -2.5981 to 2.5981 when the parameter where a=1.

The antenna should efficiently radiate or receive electromagnetic waves preferably with as high directivity (or in some cases omnidirectional pattern) and gain as possible. That goal has always conflicted with physical limitations, especially at high frequencies. Essentially, every antenna is a compromise - between resonant frequency and dimensions, efficiency and bandwidth, etc. No electrically small antenna can have high gain, large operating range and small dimensions at the same time.

The research was based on the study of this compromise, which led to very good solutions, so it is difficult for a new original design to appear.

One interesting observation was published in a monograph on wire antennas in 1985 [6]. Namely, they discovered that if they reverse the process and look at which shapes give dipoles and vertical antennas greater gain, they come to the conclusion that it is far from Euclidean geometry. Randomly bent wires or corrugated wires have been shown to give better results. The conclusion was clear, using simple geometric shapes does not always result in the best antennas.

At the end of the forties of the last century, the first frequency-independent antennas - helicoid antennas - were developed. Raymond DuHamel and Dwight Isbell from the

University of Illinois developed in 1958 a new type of frequency-independent antenna - log-periodic antenna [7]. The antenna is based on a helix that gets larger with increasing distance from the center of the helix. Today, we know that these structures are deterministic fractals [8]. Although it was common for antennas to be designed for one specific function, ie. for one frequency, or for a range of frequencies (broadband or frequency-independent antennas), with the development of devices for mass communication, there was a need for antennas that do not have to be broadband, but preferably have more resonance frequency bands and be electrically small antennas. In order to use one broadband antenna for several communication services, additional electronics (filters, adjustment circuits, etc.) are required. For these reasons, the requirements that the antenna must satisfy are complicated, so the antenna must be adapted to several bands, it must act as a filter and, which is a big challenge, to those resonant frequencies are not harmonic.

Fractal geometry is used to design multi-frequency, electrically small or highly directive antennas. One of the first examples of a multifrequency antenna is a monopole antenna based on the Sierpinski triangle. The obvious advantage of fractal antennas is that they are electrically small antennas, i.e. they are resonant occupying a small area, so there is no need to add discrete components to achieve resonance. In microwave technology, discrete components can cost more than the antenna itself. Additional parts reduce the reliability of the transmitter/receiver itself, while the antennas themselves can be made from cheap printed circuit boards. Figure 2 shows the Sierpinski monopole antenna from [9] with an illustration of the principles of self-similarity and multi-resonance.

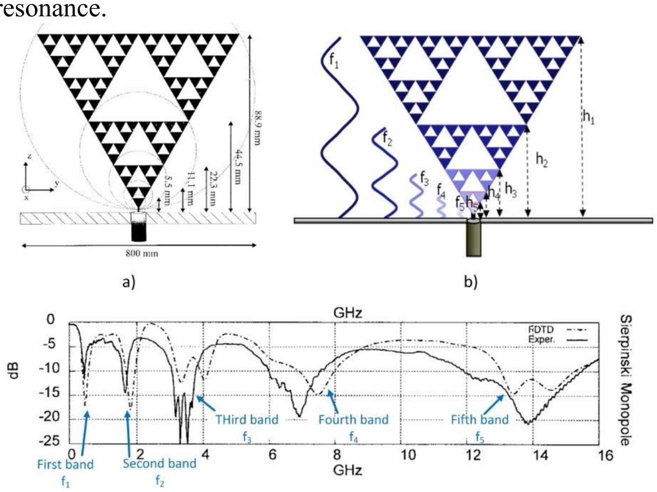

Fig. 2 Monopole antenna based on the Sierpinski triangle from [9]: a) Layout and dimensions of the antenna, b) Illustration of the frequency ranges generated by individual parts of the structure, c) Reflection coefficients and operating ranges of this antenna

The advantages of fractal antennas are: miniaturization, better adjustment of input impedance, one antenna is sufficient for several bands, either narrowband bands or broadband bands, they have stable performance over a wide range of frequencies (fractal antennas are considered frequency-independent antennas) and they are scalable. By increasing the dimensions, the resonant frequencies are proportionally reduced. If antenna arrays based on fractal geometry are used, mutual coupling will also be reduced.

Disadvantages of fractal antennas: the process of designing and manufacturing these antennas is demanding, limitations in numerical analysis, reduced gain and it is possible to use only a few iterations of fractal geometry.

Tapered Slot Antennas (TSA) were first introduced in 1979 and were linear tapered slot antennas [10]. Shortly thereafter exponentially tapered antennas known as Vivaldi antennas [11]was introduced. The degree of variation in the slot width of the Vivaldi antenna dictates the width of the main lobe of the radiation pattern. The maximum width of the slot (i.e. the widest part of the taper) corresponds to half the wavelength of the lowest frequency of the working band, while the length of the slot determines the width of the working band. For years, these antennas were popular among researchers, and various optimizations and corrections of the geometry and substrate were performed, all with the aim of obtaining the desired parameters [12]. It was these tapered antennas that served as an idea for the design of the antennas proposed in this paper.

Due to the characteristics of extremely high bandwidths and high data transfer rates, SWB technology is becoming a necessary part of modern telecommunication systems. The challenge for antenna designers is to miniaturize the antenna without degrading the bandwidth and radiation pattern. In general, the characteristics of antennas can be modified by changing the geometry, current distribution over the surface of the antenna or by changing the electrical dimensions. Antenna characteristics include input impedance matching, radiation pattern, gain, efficiency, polarization and operating range [13].

III. STATE OF THE ART

A large number of printed antennas with different materials, manufacturing techniques and geometries can be found in the literature. In general, the use of expensive substrates and fabrication techniques significantly improves the performance of antennas and thus facilitates design. On the other hand, the goal is to use cheap substrates and simple manufacturing techniques. In the papers [14]–[16], an overview and comparative analysis of current solutions in the field of fractal antenna design is given. In this chapter, a comparison of fractal printed ultra-wideband antennas made on FR4 substrate is given.

The first question that that can be asked is the use of FR-4 substrates at high frequencies. In the paper [17] a SWB hexagonal Sierpinski fractal antenna is proposed, which is made on an FR-4 substrate and operates at frequencies up to 37 GHz. The bandwidth of the antenna is 3.4–37.4 GHz, which represents a ratio of 11:1. On the other hand, the electrical area of this antenna is quite large and amounts to 0.32λ x 0.34λ. The antenna is based on a hexagonal patch with two iterations of Sierpinski square slots fed by CPW feeder. SWB antenna in the form of a propeller is presented in the paper [18]. It is made on an FR-4 substrate and operates at frequencies from 3 GHz to 35 GHz, which is a ratio of 11.6:1. The electric area of this antenna is 0.38 λ x 0.55 λ. Paper [19]

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presents a printed slot antenna based on an elliptical slot with a parasitic oval patch. The bandwidth of this antenna is from 2.26 GHz to 22.18 GHz, which is a ratio of 9.81:1. The electrical area of this antenna is 0.30 λ x 0.23λ which is significantly less than the electrical area of the previous two antennas. By adjusting the shape of the parasitic patch and the shape of the slot, broadband, multiple-resonant frequencies and fine tuning of the input impedance were achieved.

A microstrip antenna with super-broadband characteristics is proposed in [5]. The addition of semi-elliptical complementary fractal slots in the ground resulted in the suppression of currents at lower frequencies. A bandwidth of 172% was achieved, i.e. from 1.44 GHz to 18.8 GHz, which is a ratio of 12:1.

An antenna in the form of a broken heart is presented in the paper [20]. The antenna consists of a broken heart-shaped patch and a slot in the ground and has electrical dimensions of 0.27 λ x 0.17 λ and a bandwidth of 2.9 GHz to 10.7 GHz, which is a ratio of 3.69:1.

A printed antenna with increased impedance range is proposed in [21]. It operates at frequencies from 2.4 GHz to 24.3 GHz, i.e. in the range of 164 %. It is fed by CPW feeder where the ground is gradually narrowed. This ground narrowing resulted in an increase in bandwidth from 69.1% to 164% mainly by lowering the reflection coefficient at frequencies above 4 GHz.

A very interesting example of a broadband antenna is presented in the paper [22]. The antenna is designed to work in the range from 4 GHz to 10 GHz, i.e., 86 %. The area of the antenna is 0.45 λ x 0.40 λ. The same design was then adapted to operate in the range from 10 GHz to 150 GHz using a Rogers RO4232 substrate. The final optimization of the antenna achieves a bandwidth of 175% (with small modifications to the dimensions of the antenna elements and a reduction in dimensions of about 30 %).

In the paper [23], a diametrically opposed Vivaldi antenna in the form of a fern leaf was proposed. The impedance is adjusted in the width range of 19.7 GHz, i.e. from 1.3 GHz to 20 GHz. It is a fractal geometry where already in the second iteration the lower limit frequency of the range is lowered by 19%. The antenna is made on an FR-4 substrate with a thickness of 0.8 mm, and the dimensions of the antenna itself are 50.8 mm x 62 mm.

Unlike fractal patch antennas, fractal slot antennas are not so common in the literature. This is especially the case with antennas on FR-4 substrate [24][25] [26][27].

IV. Fractal ultra-wideband cardioid slot antenna

In this section, an ultra-wideband fractal slot antenna based on fractal geometry is presented. The proposed antenna has a reflection coefficient S_{11} below -10 dB in the range from 1.8 GHz to 30 GHz, due to the use of fractal geometry. Analyzing the results of fractal geometry simulations, it turns out that the first iteration of the fractal achieves the best results, i.e. ultra-wideband, while the antenna with higher fractal iterations has multiresonant characteristics. This antenna belongs to the group of electrically small antennas with electrical dimensions of just 0.21 λ x 0.285 λ. The antenna is planar, fed by CPW strip and has metallization only on one side of the substrate. The fractal geometry is in the form of a cardioid, i.e. multiple self-similar cardioids nested within each other. Fig. 3 shows the process of generating a fractal slot, where the zeroth iteration (generator) uses a slot in the form of a cardioid described by parameter a_1. It can be seen that in the following iterations the cardioids are translated along the y-axis and scaled by the coefficient a_2/a_1.

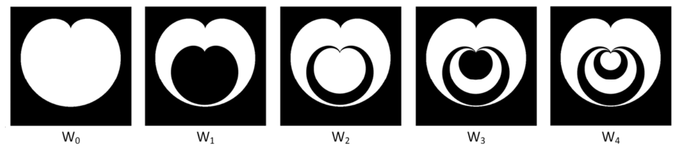

Fig. 3 Generation of fractals in the form of a cardioid with an iterative function.

The proposed antenna has three cardioids that define its structure with a CPW feed line. The parameters used to scale these cardioids, based on the equation, are: a_1, a_2 and a_3. The first two cardioids (cardioids with parameters a_1 and a_2) limit the slot, i.e. the basic element of this antenna, while the third cardioid (cardioid with parameter a_3) defines the slot located inside the monopole. CPW feeder of width W_f and length L_f with a gap fed a monopole in the form of a cardioid defined by the parameter a_2. The geometry of the proposed second-order fractal slot antenna is shown in Fig. 4.

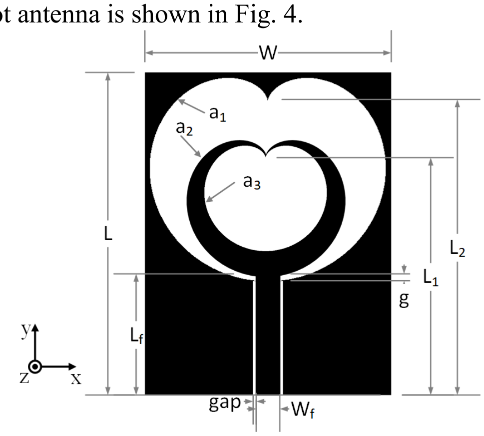

Fig. 4 Geometry of the proposed fractal antenna.

The antenna is designed for FR-4 substrate with relative dielectric constant ε_r=4.3 and tan δ=0.025. The thickness of the substrate is 1.58 mm, while the thickness of the copper metallization is 0.018 mm. In the Fig. 4 metallization is shown in black.

The geometrical parameters of the proposed antenna are W=35.1 mm, L=47.5 mm, gap=0.25 mm, W_f=2.85 mm, L_f=16.4 mm, g=0.40 mm, L_1= 34.45 mm (distance from the cardioid center), L_2= 42.43 mm, a_1=6.6, a_2=4.68 and a_3= 3.4.

The overall dimensions of the antenna are 35 mm x 47 mm x 1.61 mm, which classifies this antenna into a group of electrically small antennas [28]. The geometry of proposed antenna is shown in Fig. 4.

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In this design, although it is common to generate fractals with the same IF, a different IF is used for each iteration: $IF_1=a_2/a_1$ =0.68 and $IF_2=a_3/a_2$ =0.75. This approach allows additional flexibility when designing the antenna, which is confirmed by the results.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The antenna is manufactured using a simple photolithographic process, with a small deviation from the desired dimensions. Fig. 5. shows the produced antenna on a FR-4 substrate with a coaxial SMA connector at the input of the CPW line. The SMA connector used to feed the CPW line is declared for frequencies up to 27 GHz.

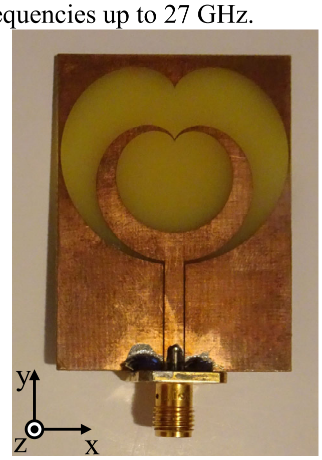

Fig. 5 Realized fractal antenna in the form of a cardioid with overall dimensions 35 mm x 47 mm

The antenna was measured using a vector network analyzer ANRITSU MS4647A. The reflection on the coaxial port of the antenna was obtained directly from the measurement results of the network analyzer. The maximum gain G_R of the antenna is obtained based on Friis formula for attenuation of free space

$$G_R = 20log_{10}d + 20log_{10}f + 20\ log_{10}4\pi / c - G_T - FSPL \quad (3)$$

where: FSPL-free space attenuation; d-distance in meters; f-frequency; c-speed of light in vacuum; G_T-gain of the transmitting antenna; G_R-gain of the receiving antenna. Ridged horn antenna was used as a transmitting antenna.

Fig. 6 shows the measurement setup with the Anritsu MS4647A network analyzer that was used to measure the antenna characteristics.

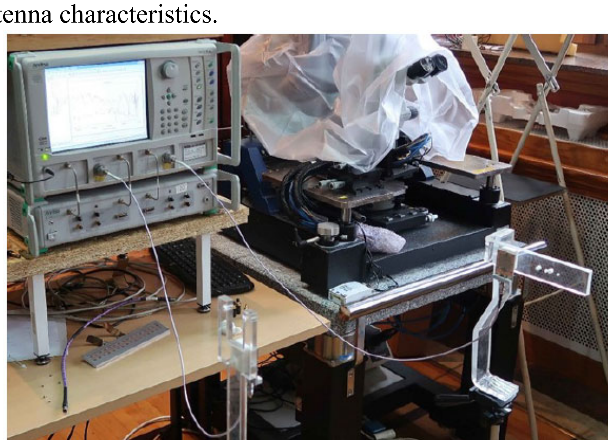

Fig. 6 Measurement setup

The measured and simulated S_{11} parameter is shown in Fig. 7.

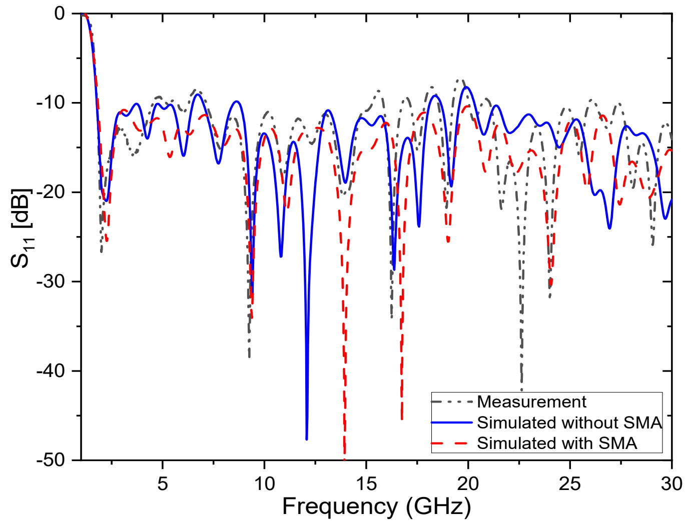

Fig. 7 Simulated and measured the reflection coefficients.

Based on the results shown in the Fig. 7, it can be seen that the results of the measurements and simulations match quite well. One of the reasons for the discrepancies between the measured and simulated results is the manufacturing process. Namely, as a result of using a cheap photo-lithography process, there were minor discrepancies in the dimensions of the designed and manufactured antenna. It was precisely the goal to show that even with manufacturing inaccuracy, this antenna works in the designed super-broadband range. Another reason for the discrepancy in results is the properties of the FR-4 substrate. Namely, considering that FR-4 is a cheap substrate, the relative dielectric constant is not strictly controlled and can vary from one sheet of FR-4 substrate to another and from one manufacturer to another. The thickness of the substrate also does not have to be precise.

Considering that the antenna can only be measured using the SMA connector (although the antenna itself can be directly integrated on the board with electronics), in order to eliminate doubts about the influence of the SMA connector on the results of measurements and simulations, Fig. 7 shows the simulation results with and without SMA connectors. Based on the results from the picture, it can be seen that there are discrepancies above 20 GHz, but the reflection coefficient is below -10 dB with or without the connector, which clearly shows that the SMA connector, in this project, can be used up to 30 GHz without affecting the reflection coefficient.

Fig. 8. shows the results of measurements and simulations of the gain calculated by expression (3). The gain was only measured up to 6 GHz because we had a transmitting antenna that is declared in that band.

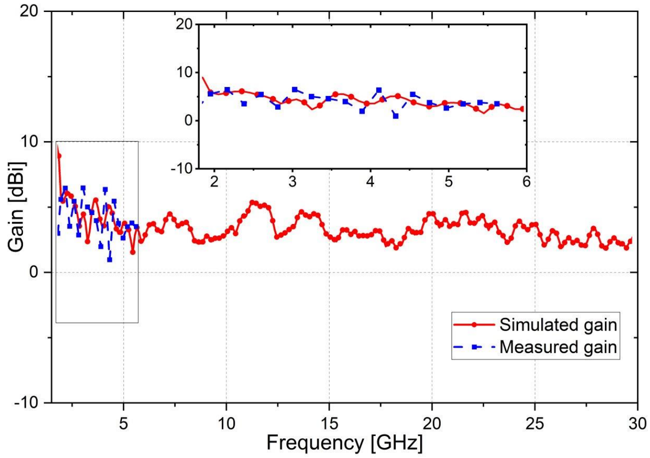

Fig. 8 Measured and simulated gain of the proposed antenna.

The proposed antenna is compared with previously reported super wideband (SWB) antennas on FR-4 substrate in terms of operating bandwidth (BW), electrical dimensions and *bandwidth dimension ratio (BDR)*. The results are shown in Table 1. The bandwidth dimension ratio indicates how large the operating bandwidth is as a percentage per antenna electrical area unit [5]:

$$BDR = \frac{BW_{\%}}{L_{f_{low}} \times W_{f_{low}}} \tag{4}$$

where $L_{f_{low}}$ represents the electrical length and $W_{f_{low}}$ electrical width of the antenna calculated at the lower-end of operating band that meets the -10dB return loss, and $BW_{\%}$ represents bandwidth in percentage calculated by the formula:

$$BW_{\%} = 2\left(f_{high} - f_{low}\right) / \left(f_{high} + f_{low}\right) \cdot 100\% \tag{5}$$

where f_{low} and f_{high} represent the lower and higher frequency of operating band respectively. A larger BDR indicates that designed antenna is smaller in dimension and wider in bandwidth.

TABLE 1
COMPARISON OF SWB ANTENNA STRUCTURES FABRICATED ON FR-4 SUBSTRATE IN TERMS OF VARIOUS PARAMETERS

Reference	Freq. range (GHz)	BW :1	BW %	Electrical dimensions*	BDR
[5]	1.4-18.8	13.0:1	172%	0.17 λ x 0.37 λ	2762.66
[17]	3.4-37.4	11.0:1	167%	0.32 λ x 0.34 λ	1544.73
[20]	2.9-10.7	3.6:1	115%	0.16 λ x 0.29 λ	2406.92
[18]	3-35	11.6:1	168%	0.38 λ x 0.55 λ	805.84
[19]	2.2-22.1	9.8:1	163%	0.30 λ x 0.23 λ	2393.66
[21]	2.4-24.3	10.1:1	164%	0.18 λ x 0.33 λ	2718.13
[29]	2.9-18	6.2:1	144%	0.29 λ x 0.29 λ	1718.16
[30]	3-11.2	3.7:1	115%	0.22 λ x 0.24 λ	2187.36
Proposed	1.8-30	**16.9:1**	**178%**	0.21 λ x 0.28 λ	**3062.09**

* Electrical dimensions are calculated relative to the lowest frequency in the band

Based on the comparative results shown in Table 1, it can be seen that the proposed antenna has better characteristics than the existing solutions from the literature.

Fig. 9. shows a comparison of simulated and measured radiation patterns in the E- and H-planes at the following frequencies: 1.8; 2.2; 2.4; 3.4, 5.8 and 10 GHz.

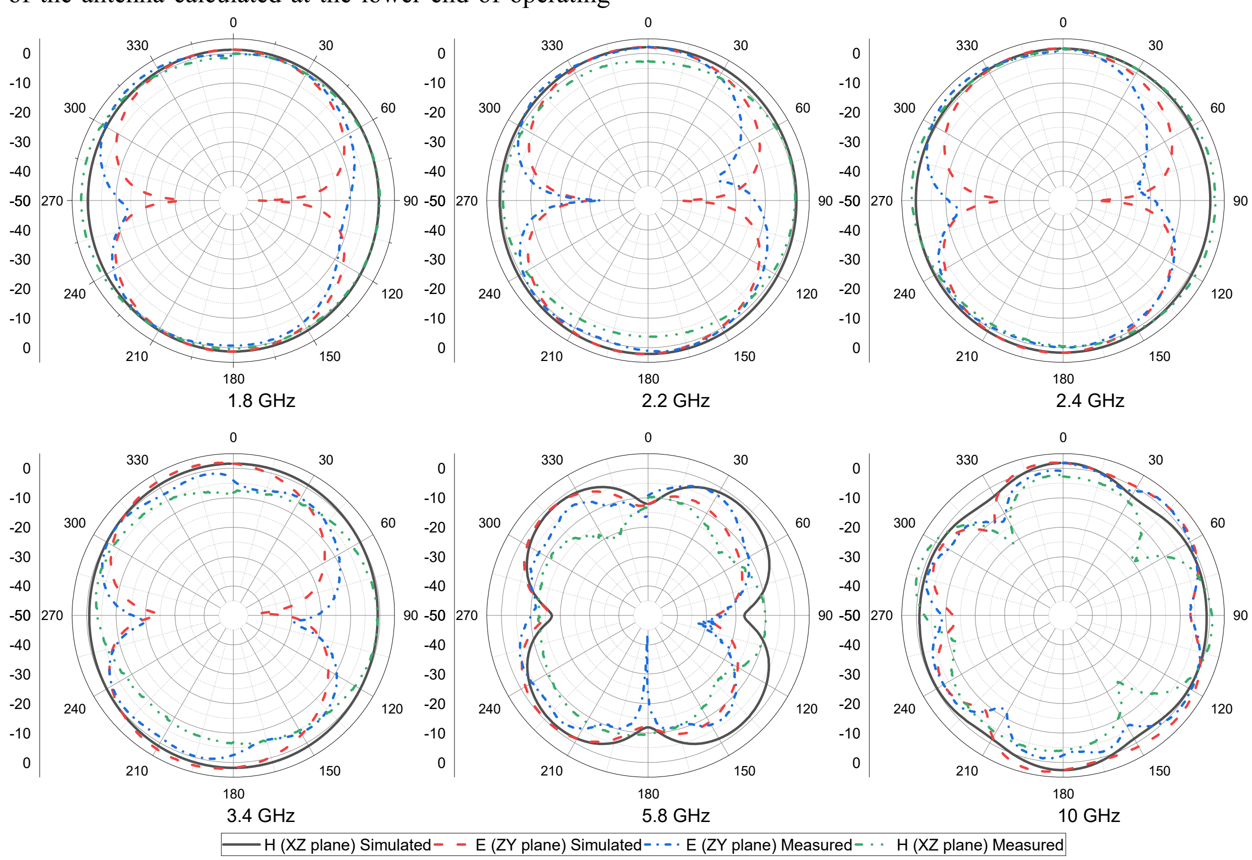

Fig. 9 Measured and simulated radiation patterns in the E- and H-planes.

Based on the measurement results shown in Fig. 9, an extremely good match of the simulated and measured radiation patterns can be noted. 3D radiation diagrams in the logarithmic scale shown in Fig. 10.

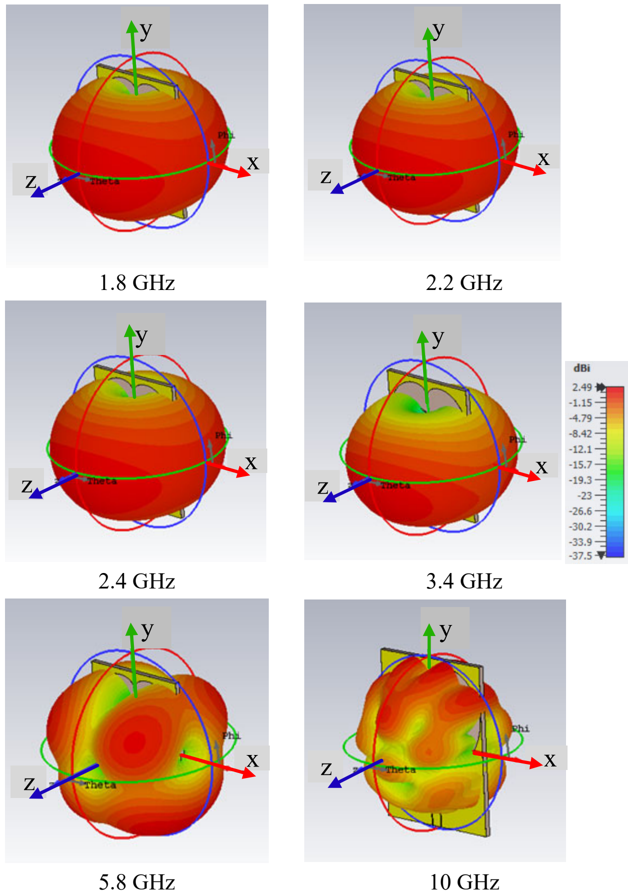

Fig. 10 3D representation of the simulated radiation patterns.

A. Antenna scalability

The scalability of the antenna itself is a rarity when it comes to antennas with complex geometry. Antennas with simple geometries, such as a dipole, are scalable, i.e., directly proportional to the wavelength. Analyzing the bandwidth, especially its lower limit, it was observed that by proportionally increasing the dimensions of the antenna (except for the thickness of the antenna), the entire working range can be moved downwards.

The antenna is primarily intended for EH where most of the ambient electromagnetic energy is concentrated in the range from 1.8 GHz to 5.8 GHz (3G, 4G, 5G, Wi-Fi, Bluetooth and ISM, as well as IoT and WSN bands). The antenna, in that range, has an omnidirectional radiation pattern. If necessary, the range of frequencies where the antenna has an omnidirectional radiation pattern can be changed by scaling the dimensions of the antenna (which will affect the deterioration of the bandwidth, especially at lower frequencies).

One way to improve the radiation pattern, which essentially increases the quality of this design, is to reduce the dimensions of the antenna. Antennas with a 30% reduction in dimensions are simulated, and there appear omnidirectional radiation patterns above 20 GHz, but the operating range in which the impedance is adjusted at low frequencies is reduced from 1.8 to 2.6 GHz (from 16:1 to 11:1).

Fig. 11 shows the reflection coefficients in cases where the antenna is scaled to 70 %, 80 %, 120 % and 130 % of the original dimensions. Reducing the antenna to 80 % of the original dimensions increases the range of frequencies in which the radiation pattern is omnidirectional.

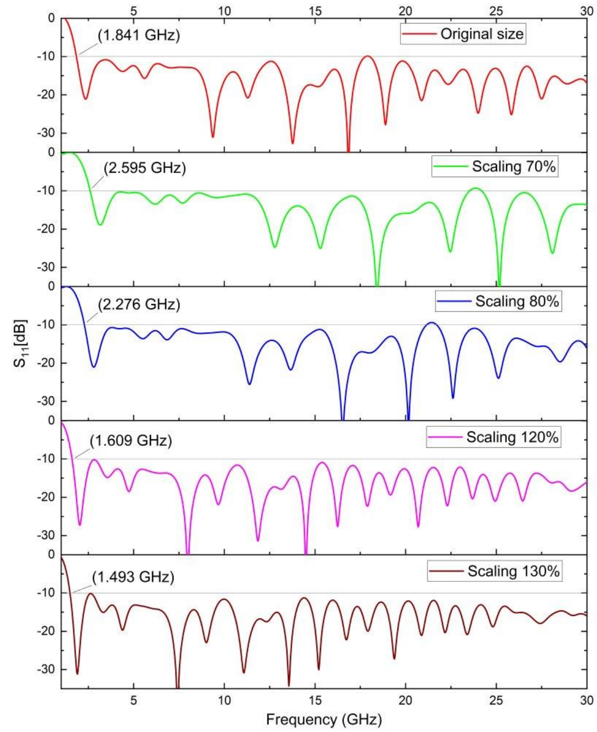

Fig. 11 Reflection parameters for different dimensions of the scaled antenna

B. Antenna arrays

Antenna arrays are widely used in modern communication systems to increase diversity as well as EH systems to increase efficiency. In addition to this, the increase in directivity achieved by arrays is also beneficial. Considering its application in EH systems, knowing that the received energy density on the surface of the antenna is very small, making linear and planar arrays is very important because this way increases the efficiency of the system [31][32].

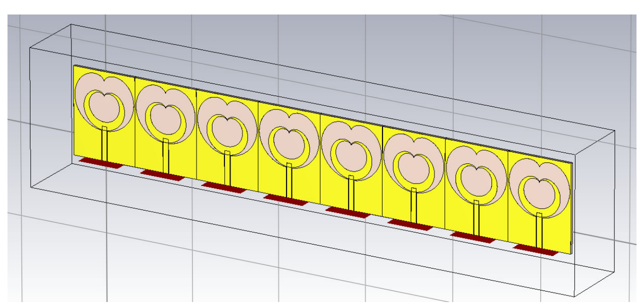

Fig. 12 Antenna array with 8 elements

The results of simulations for uniform equidistant arrays with 4 and 8 antennas (Fig. 12) at the frequency 5.8 GHz are shown in the Fig. 13. The distance of antennas in a row is 0.7 λ_0 (35.7 mm). This, can be one way to correct scattered radiation patterns. The simulations were performed in the

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electromagnetic simulator at CST, taking into account the mutual coupling and not only the array factor. The layout of an array with 8 elements is shown in the Fig. 12.

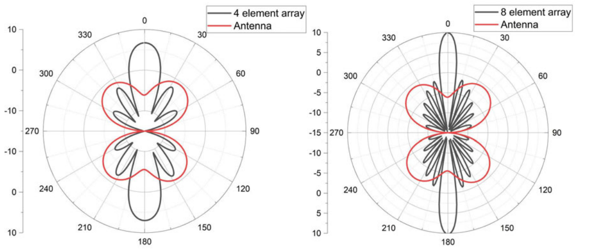


Fig. 13 Radiation diagrams of arrays at a distance of 0.7 λ_0 with 4 elements and with 8 elements

The results of the simulations show that the directivity of the system is significantly increased and that the problem of side lobes of the radiation diagram is solved. Side lobe suppression of 13 dB was achieved.

In case this antenna is used in communication systems, its use in MIMO systems is possible. Figure 14 shows S_{21} parameters (Fig. 14 c) when two antennas are at a distance of 40mm (Fig. 14 a) and when they are at a distance of 11mm but one antenna is rotated by 90º (Fig. 14 b). Given that the coefficients S_{21} under -20 dB, the conclusion is that the antenna can be used in MIMO systems.

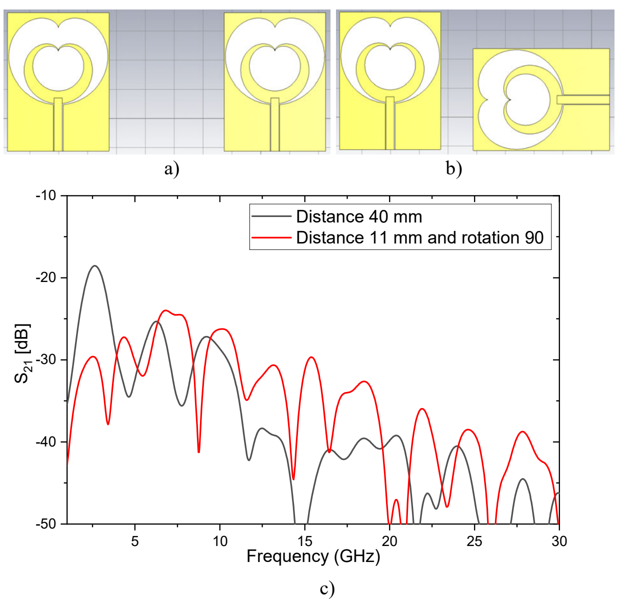


Fig. 14 a) Antennas at distance 40 mm, b) Antennas at distance of 11mm and rotated by 90º, c) Simulated S_{21} parameters in case of two MIMO configuration

C. *Antenna with planar reflector*

Ambient electromagnetic energy is often not present from all directions, i.e., it does not fall on the antenna from all directions, for example, in the case of satellite communications, or radar signals. In those cases, the electromagnetic energy is directed (especially at higher frequencies), so there is no need to receive energy omnidirectionally. Then it would be desirable to increase the directivity and receive energy only from one side of the antenna. This is achieved either by using arrays (only increasing the directivity but not canceling the background radiation) or by using planar reflectors. Reflectors placed at a certain distance behind the antenna will increase the directivity and therefore the amount of collected electromagnetic energy from only one side of the antenna.

One of the examples of reflectors is shown in Fig. 15. In this case, the reflector is placed at a distance $\lambda_0/4$ behind the antenna. The dimensions of the reflector in this case are 3Wx3L.

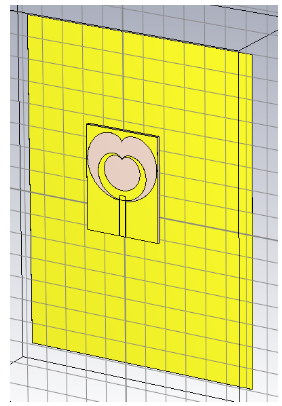


Fig. 15 Reflector is placed at the distance $\lambda_0/4$ behind the antenna. The dimensions of the reflector in this case are 3W x 3L

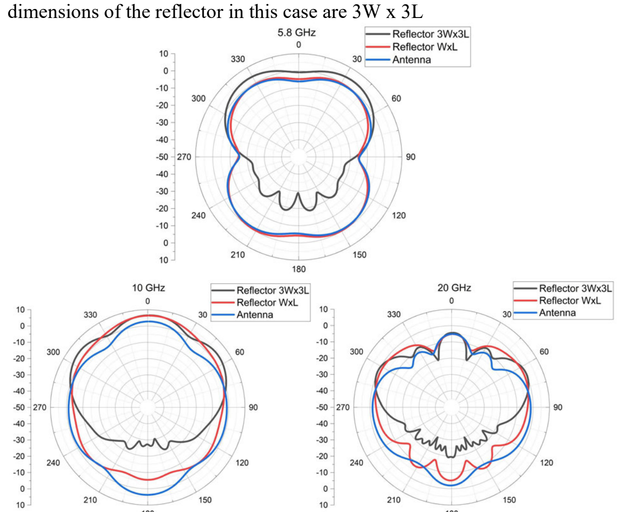


Fig. 16 Comparative radiation diagrams of the antenna with and without reflectors with dimensions *2W*x*3L* and *W*x*L* at a distance $\lambda_0/4$ behind the antenna for frequencies 5.8 GHz, 10 GHz and 20 GHz.

Based on the results of the simulations shown in the Fig. 16, it can be seen that the improvement of the radiation diagram, its direction and the increase of amplification by 5 dB. Of course, reflectors can also be used in combination with arrays.

VI. Antenna for Power Harvesting

The designed antenna is intended for the application in wideband energy harvesting systems that do not use an impedance matching circuit as part of the rectenna. In order to eliminate the matching network in rectenna design, the input impedance of the antenna should be equal to the complex conjugate value of the diode impedance. The real and imaginary parts of the antenna impedance, simulated and measured complex conjugate value of the SMS 7630 diode impedance are shown in Fig. 13 and 14. Simulated values of the antenna impedance are compared with the measured and simulated complex conjugate diode impedance reported in [33]. Impendence simulation are obtained via Harmonic Balance simulation for different values of RF input power and different values of load resistance [33]. When designing an antenna care was taken that the input impedance of the antenna, at the place where the diode is connected, is approximately equal to its optimal input impedance. Based on current distribution over the antenna surface it can be seen that an optimal place for diode mounting on antenna surface is shown on Fig. 15a.

The simulation results show a good impedance matching at the very small input powers, which makes this antenna very efficient.

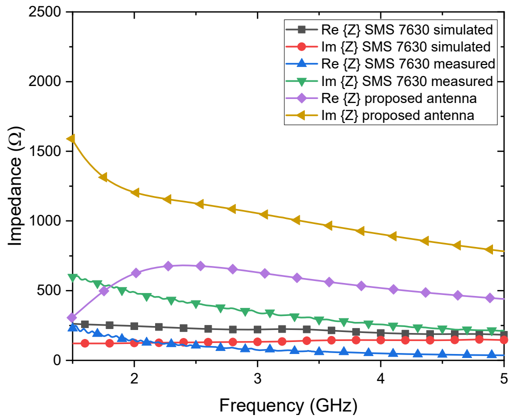
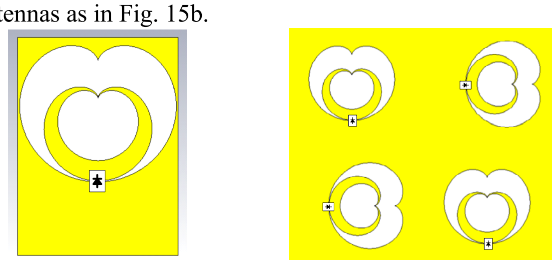


Fig. 17 Simulated impedance of the proposed antenna compared to the simulated and measured complex conjugate impedance of SMS 7630 diode with load impedance R_{LOAD}=3 kΩ and input power P_{IN}=0 dBm.

The proposed rectenna is intended, among other things, for use in EH applications. It can be used alone, Fig. 15a, or as part of rectenna arrays to increase its efficiency [34]. Fig. 16 shows a planar rectenna array. The highest efficiency in energy harvesting is achieved when the array has a dual polarization, which in this case can be done by grouping the antennas as in Fig. 15b.



(a) (b)

Fig. 18 Rectenna (a) and arrays of rectennas with dual polarization (b) for EH applications

VII. Fractal ultra-wideband cardioid-shaped monopole antenna

In this chapter, an ultra-wideband fractal monopole antenna based on cardioid geometry is presented. The simulation results show that the antenna has S_{11} below -10 dB in the range from 4 GHz to 30 GHz, covering almost the entire SHF range. Additionally, the antenna has a gain of up to 5.5 dBi and an efficiency of up to 80 %.

The antenna was designed in CST (Time domain solver), while optimization of dimensions and parametric analysis was done mainly by trial-and-error method. In the case of using this antenna in ambient electromagnetic energy collection systems, the antenna is designed for rectenna that do not have a matching circuit, but the diode itself is mounted directly on the antenna.

The proposed antenna has two cardioids that define its structure. The parameters used to scale these cardioids, a_1 and a_2. This antenna belongs to the group of patch antennas and is fed by microstrip feeder of width W_f and length L_f. The patch itself and the microstrip feed line are not placed symmetrically with respect to the substrate but are slightly shifted to the right for better impedance matching. The geometry of the proposed fractal slot antenna of the first order is shown in Fig. 19.

The antenna is designed for FR-4 substrate with relative dielectric constant ε_r=4.3 and loss angle tangent tan δ=0.025. The thickness of the substrate is 1.58 mm, while the thickness of the copper metallization is 0.018 mm. In Fig. 19 the metallization on the upper side of the substrate is shown in black and on the lower side of the substrate it is shown in gray. The overall dimensions of the antenna are 18 mm x 25 mm x 1.61 mm. This antenna belongs to the group of electrically small antennas.

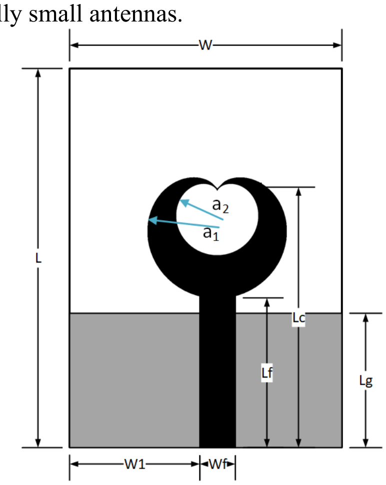


Fig. 19 Geometry of the proposed fractal antenna

The dimensions of the antenna are: a_1=1.84, a_2=0.92, W=18.5 mm, L=25 mm, W_f=2 mm, W_1=9.14 mm, L_g=9.13 mm, L_f=10.5 mm, L_c=17.6 mm (distance from the center of the cardioid).

Fig. 20 shows the results of the simulations in the extended band from 2 GHz to 30 GHz, where it can be seen that the antenna radiates in almost the entire SHF band.

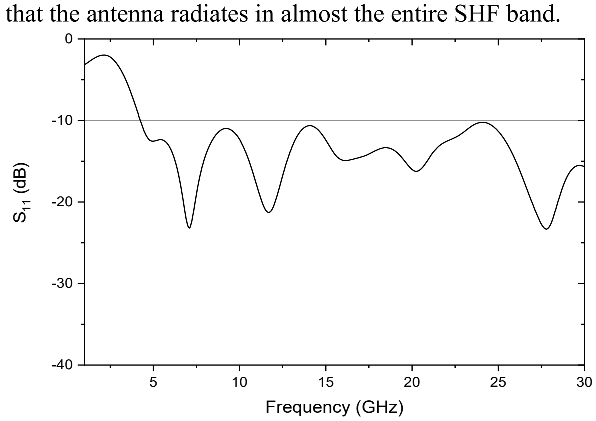


Fig. 20 The simulated reflection coefficients in SHF band.

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Fig. 21 shows the radiation patterns of the proposed antenna at 2 GHz, 6.5 GHz and 11.8 GHz.

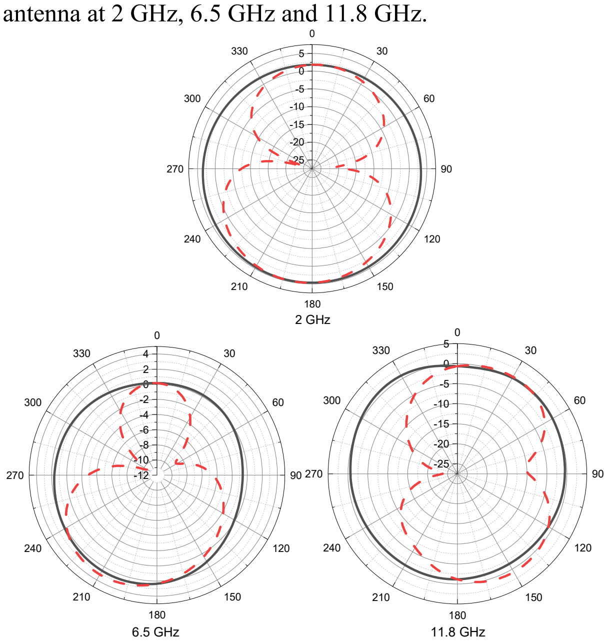

Fig. 21 Radiation patterns of the proposed antenna at 2 GHz, 6.5 GHz and 11.8 GHz in E-Plane (solid line) and H-Plane (dotted line).

The search for optimal antenna dimensions was achieved by parametric analysis by trial-and-error method. As parameters, the dimensions of ground plane and cardioids dimensions were changed, i.e., the ratio of larger and smaller cardioids.

In order to eliminate matching network in rectenna design, the optimal input impedance of the diode should be equal to complex conjugate value of the diode impedance. In [33], the optimal diode impedance of SMS 7630 zero bias Schottky diode was reported. The real and imaginary parts of the antenna impedance are shown on Fig. 22.

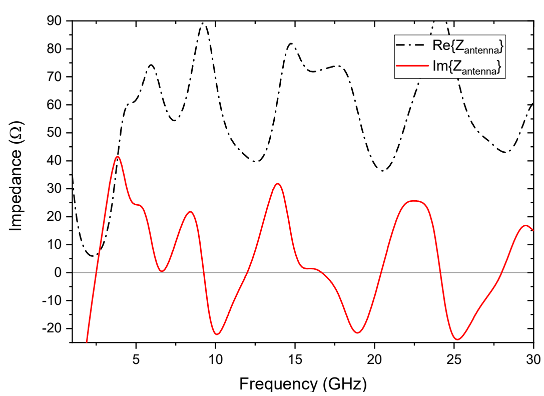

Fig.22 Impedance of the proposed antenna.

From Fig. 22. it can be seen that the proposed antenna has inductive impedance in large part of observed range, which corresponds to optimal impedance of SMS 7630 zero bias Schottky diode reported in [33]. In addition, proposed antenna has inductive impedance in: 2.58-9.02 GHz, 12.05-16.16 GHz, 20.17-23.84 GHz and 27.50-32.25 GHz ranges.

Fig. 23. shows the gain and the efficiency of proposed antenna. As expected, the gain increases when frequency increases.

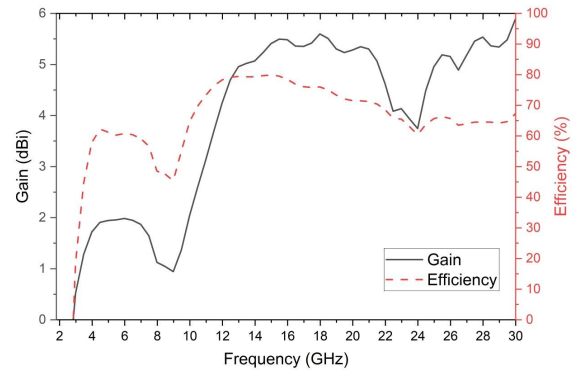

Fig. 23 The gain and efficiency of the proposed antenna.

From Fig. 9. it can be seen that at higher frequencies the antenna has an efficiency up to 80%.

From the Fig. 24 it can be seen that the proposed antenna is scalable, i.e., that a proportional reduction in dimensions (except, of course, substrate thickness and metallization) shifts the range down or up. If it is necessary to adjust the antenna to work at lower frequencies, this is possible by increasing the dimensions, but at the expense of reducing the antenna's operating range. Unlike the previous antenna, changing the dimensions of this antenna distorts the S_{11} values.

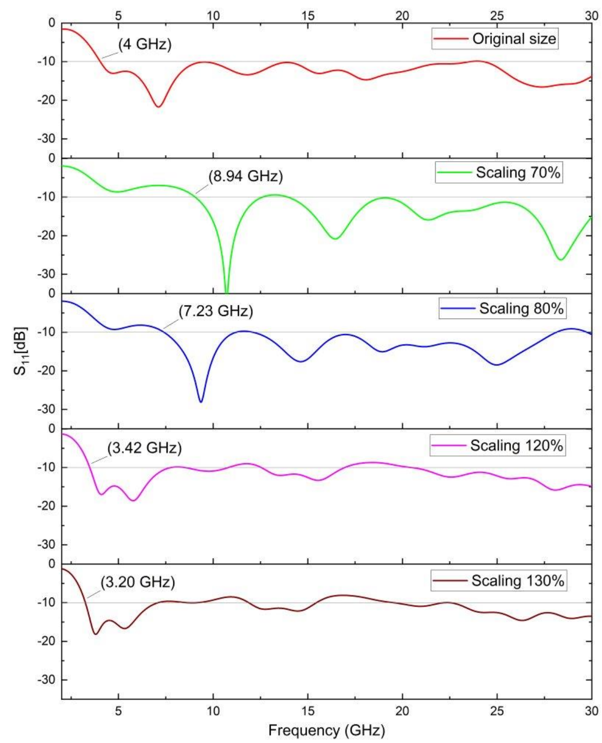

Fig. 24 Comparative analysis of the original and scaled antennas (70%, 80%, 120% and 130%)

VIII. Conclusion

In this paper a review and recent developments of fractal antennas is presented. Also, the original design of two ultra-wideband fractal antennas based on cardioid is shown. The antennas are suitable for mass and cheap production and can be used either as a separate device or integrated with other sub devices of a telecommunication system in the wide-band frequency range.

The first proposed antenna is a uniplanar fractal slot antenna fed by CPW feeder operating in the range of 1.8 GHz to 30 GHz, with extremely small electrical dimensions of only 0.21 λ x 0.285 λ at the lowest frequency of 1.8 GHz. Comparing this antenna with antennas from the literature, it was found that proposed antenna has the highest bandwidth dimension ratio (BDR). Experimental verification of the antenna parameters confirmed the results of the simulations. Simulations have shown that the antenna has a reflection coefficient S_{11} below -10 dB in the entire range from 1.8 GHz to 30 GHz, which covers all existing commercial bands for 3G, 4G, 5G, Wi-Fi, ISM, satellite communications and radars. The antenna achieves a gain of up to 5 dBi.

The second antenna is a monopole antenna, where we have double-sided printing on the FR-4 substrate. The antenna has a working range from 4 GHz to 30 GHz, it is electrically small antenna with efficiency up to 80 %. In addition to these characteristics, both antennas have an input impedance that matches the conjugate complex impedance of the Schottky diode, that is important for applications in energy harvesting systems.

REFERENCES

[1] W. Fan *et al.*, "A Step Toward 5G in 2020: Low-cost OTA performance evaluation of massive MIMO base stations.," *IEEE Antennas Propag. Mag.*, vol. 59, no. 1, pp. 38–47, Feb. 2017, doi: 10.1109/MAP.2016.2630020.

[2] L. Lazović, B. Jokanovic, V. Rubežić, M. Radovanovic, and A. Jovanović, "Fractal Cardioid Slot Antenna for Super Wideband Applications," *Electronics*, vol. 11, no. 7, p. 1043, Mar. 2022, doi: 10

[3] Benoît Mandelbrot, *The Fractal Geometry of Nature*. W. H. Freeman and Co., 1982.

[4] Kenneth A. Falconer, *Fractal Geometry: Mathematical Foundations and Applications*. Wiley, 1990, 1990.

[5] Ke-Ren Chen, C. Sim, and Jeen-Sheen Row, "A Compact Monopole Antenna for Super Wideband Applications," *IEEE Antennas Wirel. Propag. Lett.*, vol. 10, pp. 488–491, 2011, doi: 10.1109/LAWP.2011.2157071.

[6] F. M. Landstorfer and R. R. Sacher, *Optimisation of wire antennas*. Research Studies Press, 1985.

[7] R. DuHamel and D. Isbell, "Broadband logarithmically periodic antenna structures," in *IRE International Convention Record*, Mar. 1958, vol. 5, pp. 119–128. doi: 10.1109/IRECON.1957.1150566.

[8] J. Kraus, *Antennas 3rd edition*. Mcgraw Hill Higher Education, 2001.

[9] C. Puente-Baliarda, J. Romeu, R. Pous, and A. Cardama, "On the behavior of the sierpinski multiband fractal antenna," *IEEE Trans. Antennas Propag.*, vol. 46, no. 4, pp. 517–524, 1998,

[10] S. N. Prasad and S. Mahapatra, "A Novel MIC Slot-Line Antenna," in *9th European Microwave Conference, 1979*, Oct. 1979, pp. 120–124..

[11] P. J. Gibson, "The Vivaldi Aerial," in *1979 9th European Microwave Conference*, Sep. 1979, pp. 101–105.

[12] A. Bhattacharjee, A. Bhawal, A. Karmakar, A. Saha, and D. Bhattacharya, "Vivaldi antennas: a historical review and current state of art," *Int. J. Microw. Wirel. Technol.*, vol. 13, no. 8, pp. 833–850, Oct. 2021, doi: 10.1017/S1759078720001415.

[13] C. A. Balanis, *Antenna Theory - Analysis and Design*, Fourth. Wiley, 2016.

[14] J. Anguera *et al.*, "Fractal antennas: An historical perspective," *Fractal Fract.*, vol. 4, no. 1, pp. 1–26, 2020, doi: 10.3390/fractalfract4010003.

[15] N. Sharma and S. S. Bhatia, "Comparative analysis of hybrid fractal antennas: A review," *Int. J. RF Microw. Comput. Eng.*, vol. 31, no. 9, Sep. 2021, doi: 10.1002/mmce.22762.

[16] A. Karmakar, "Fractal antennas and arrays: A review and recent developments," *Int. J. Microw. Wirel. Technol.*, vol. 13, no. 2, pp. 173–197, Mar. 2021, doi: 10.1017/S1759078720000963.

[17] S. Singhal and A. K. Singh, "CPW-fed hexagonal Sierpinski super wideband fractal antenna," *IET Microwaves, Antennas Propag.*, vol. 10, no. 15, pp. 1701–1707, Dec. 2016, doi: 10.1049/iet-map.2016.0154.

[18] A. Gorai, A. Karmakar, M. Pal, and R. Ghatak, "A CPW-Fed Propeller Shaped Monopole Antenna With Super Wideband Characteristics," *Prog. Electromagn. Res. C*, vol. 45, no. August, pp. 125–135, 2013, doi: 10.2528/PIERC13082805.

[19] M. C. Tang, R. W. Ziolkowski, and S. Xiao, "Compact hyper-band printed slot antenna with stable radiation properties," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 2962–2969, 2014, doi: 10.1109/TAP.2014.2314299.

[20] N. Rahman, M. T. Islam, Z. Mahmud, and M. Samsuzzaman, "The Broken-Heart Printed Antenna for Ultrawideband Applications: Design and Characteristics Analysis," *IEEE Antennas Propag. Mag.*, vol. 60, no. 6, pp. 45–51, Dec. 2018, doi: 10.1109/MAP.2018.2870664.

[21] C. Deng, Y. J. Xie, and P. Li, "CPW-fed planar printed monopole antenna with impedance bandwidth enhanced," *IEEE Antennas Wirel. Propag. Lett.*, vol. 8, pp. 1394–1397, 2009, doi: 10.1109/LAWP.2009.2039743.

[22] T. Goel and A. Patnaik, "Novel Broadband Antennas for Future Mobile Communications," *IEEE Trans. Antennas Propag.*, vol. 66, no. 5, pp. 2299–2308, 2018, doi: 10.1109/TAP.2018.2816660.

[23] B. Biswas, R. Ghatak, and D. R. Poddar, "A Fern Fractal Leaf Inspired Wideband Antipodal Vivaldi Antenna for Microwave Imaging System," *IEEE Trans. Antennas Propag.*, vol. 65, no. 11, pp. 6126–6129, Nov. 2017, doi: 10.1109/TAP.2017.2748361.

[24] D.-C. Chang, B.-H. Zeng, and J.-C. Liu, "CPW-Fed Circular Fractal Slot Antenna Design for Dual-Band Applications," *IEEE Trans. Antennas Propag.*, vol. 56, no. 12, pp. 3630–3636, Dec. 2008, doi: 10.1109/TAP.2008.2007279.

[25] S. Dhar, S. Maity, B. Gupta, D. R. Poddar, and R. Ghatak, "A CPW fed slot loop Minkowski fractal antenna with enhanced channel selectivity," in *2012 International Conference on Communications, Devices and Intelligent Systems (CODIS)*, Dec. 2012, pp. 542–545. do

[26] V. Ugendra, H. Khan, B. T. P. Madhav, and C. Joshna, "Multiband Fractal Slot Antenna with Closed Ground Structure," in *Smart Computing and Informatics: Proceedings of the First International Conference on SCI 2016, Volume 2 (Smart Innovation, Systems and Technologies*, Springer, Singapore., 2018, pp. 75–83. doi: 10.1007/978-981-10-5547-8_8.

[27] D. D. Krishna, M. Gopikrishna, C. K. Anandan, P. Mohanan, and K. Vasudevan, "CPW-Fed Koch Fractal Slot Antenna for WLAN/WiMAX Applications," *IEEE Antennas Wirel. Propag. Lett.*, vol. 7, pp. 389–392, 2008, doi: 10.1109/LAWP.2008.2000814.

[28] L. Lazović, B. Jokanovic, V. Rubežć, and A. Jovanović, "Uniplanar Ultra-Wideband Cardioid Slot Antenna for Energy Harvesting Application," in *2019 27th Telecommunications Forum (TELFOR)*, 2019, pp. 1–4.

[29] M. R. Ghaderi and F. Mohajeri, "A compact hexagonal wide-slot antenna with microstrip-fed monopole for UWB application," *IEEE Antennas Wirel. Propag. Lett.*, vol. 10, pp. 682–685, 2011,

[30] R. Azim, M. T. Islam, and N. Misran, "Compact tapered-shape slot antenna for UWB applications," *IEEE Antennas Wirel. Propag. Lett.*, vol. 10, pp. 1190–1193, 2011, doi: 10.1109/LAWP.2011.2172181.

[31] J. A. Hagerty, S. Member, F. B. Helmbrecht, W. H. Mccalpin, R. Zane, and Z. B. Popovic, "Broad-Band Rectenna Arrays," *Ieee Trans. Microw. Theory Tech. Vol. 52, No. 3, March 2004*, vol. 52, no. 3, pp. 1014–1024, 2004.

[32] Z. Popovic *et al.*, "Scalable RF Energy Harvesting," *IEEE Trans. Microw. Theory Tech.*, vol. 62, no. 4, pp. 1046–1056, Apr. 2014, doi: 10.1109/TMTT.2014.2300840.

[33] B. Milosevic, M. Radovanovic, and B. Jokanovic, "Measurement of rectifying diode impedance and efficiency for energy harvesting applications," in *EUROCON 2019*, 2019, pp. 1–5.

[34] J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane, and Z. B. Popovic, "Recycling Ambient Microwave Energy With Broad-Band Rectenna Arrays," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 3, pp. 1014–1024, Mar. 2004, doi: 10.1109/TMTT.2004.823585.

 ISBN 978-86-7466-970-9