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Design and Implementation of Multi-Band Fractal Slot Antennas for Energy Harvesting Applications

Ahmed M. A. Sabaawi[1]*, Qusai H. Sultan[1], Tareq A. Najm[1]

[1] College of Electronics Engineering, Ninevah University, Al-Jawsaq, Right Coast, 41002 Ninewa, Mosul City, Iraq
* Corresponding author, e-mail: ahmed.sabaawi@uoninevah.edu.iq

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Abstract

This paper introduces a design and optimization procedure of multiband fractal slot antennas for RF energy harvesting applications. The antennas were simulated using CST Studio Suite. A parametric study is conducted to determine the critical structural parameters that influence the antenna performance. The parametric study included varying the size ratio of the structure, the shape of the ground plane and the length of the feeding inset. Simulation results showed that the proposed antennas in this work exhibit multiband performance and they offer the possibility of controlling the resonant frequency at any specific frequency band. The optimized antenna has seven resonant frequencies at 1.8 GHz, 2.4 GHz, 3.45 GHz, 3.6 GHz, 4 GHz, 4.6 GHz and 5.3 GHz covering several ambient communication networks (GSM, UMTS and 5G), Bluetooth and WLAN systems. Simulation results shows that Antenna 1 has achieved a gain of more than 4.5 dBi at all the resonant frequencies with a radiation efficiency ranged between 87%–95%; whereas Antenna 2 has achieved more than 3 dBi gain at lower frequencies while reaching around 7 dBi at higher frequencies with a radiation efficiency ranged between 80%–97%. Finally, two fractal slot antennas were fabricated and tested in the lab to validate the simulation results and to proof the concept of the feasibility of this type of antennas for this application. Experimental results showed a good agreement with simulations.

Keywords

antennas, fractal loops, energy harvesting, multiband

1 Introduction

The last few decades have witnessed a rapid advancements in ultra-low-power integrated circuits as well as the emergence of new Internet of Things (IoT) applications. These recent advancements have made the ambient energy harvesting technologies a promising approach to power up sensing nodes and low power communication devices for domestic and medical applications. It also helps to reduce costs associated with battery replacements and energy-related repairs. Thus, by employing ambient RF energy harvesting systems, it is now possible to power electronic devices without the need for batteries or any other predesigned sources [1]. A typical wirelessly powered system should be ultra-low-power and composed of RF front end for energy harvesting, power and storage management unit, and a low-power circuitry (i.e a microprocessor and/or transceiver). The aforementioned interest in RF energy harvesting systems is aligned with the rapidly increasing demand for portable wireless devices operating in L, S and C frequency bands [2].

Most of current RF energy harvesting devices are designed and optimized for a single frequency band. Thus, a single RF circuit is individually tuned at a given frequency band, where such multiple circuits are needed to cover other distinct bands. From this point, there is a need to overcome the challenge of limited capability in harvesting ambient RF energy from different frequency bands utilizing a single RF circuit. This will increase the simplicity of the system, where only one rectifier integrated to a multiband matching network is needed per one antenna leading to a compact size, low cost and low overall complexity.

Rectifying antennas (rectennas) have received a significant interest by researchers as an important part in RF energy harvesting devices that enable powering battery-free wireless nodes and networks. They play a key role in modern RF energy harvesting and wireless power transfer (WPT) systems as they directly influence the amount of direct current (DC) power delivered to the targeted load. The antenna element is a critical part in

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achieving a high radiation-to-ac efficiency, which has a direct impact on the RF-to-DC efficiency by orders of magnitude [2].

The low RF power density is one of the main limitations of energy harvesting systems that leads to a low RF-to-DC efficiency. Thus, In order to reach a high conversion efficiency, a careful attention should be paid towards the antenna design with a special focus on the antenna's radiation properties as well as the antenna-rectifier impedance matching.

Recently, various multiband antennas have been proposed in the literature for RF energy harvesting where multiple RF sources are available such as GSM, Bluetooth, WLAN, LTE, UMTS and 5G network. Some of the previously reported antenna are operating at a single frequency band [3–5]. In addition, triple-band antennas have been widely reported in the literature with the aim to increase the overall system efficiency and reduce the rectifier complexity [6–9].

Furthermore, wideband and multiband antennas for RF energy harvesting systems are dominating the literature covering various available RF sources and mobile networks. These designs include triangular patch antennas with defected ground plane [10], quad-band circular antennas [11], slit bow-tie antennas for IoT applications [12] and annular slot antenna operating at LTE frequency bands [13]. Finally, the wideband and multiband properties of fractal antennas were efficiently employed in this application to maximize the conversion efficiency and to explore as many RF sources as possible such as WiMax [14] and the UWB frequency bands [15, 16] and other applications and mobile networks [17–20].

In this paper, new multiband fractal slot antennas with partial ground plane have been proposed for RF energy harvesting systems covering the frequency bands from 1–6 GHz including GSM, LTE, UMTS, WLAN and 5G networks. The proposed antennas were fabricated and tested in the lab and their performance was measured and compared with each other to find out the better characteristics. The aim of this paper is to serve as guideline for fractal antennas design and construction and their feasibility for energy harvesting applications by focusing on the most important geometrical parameters that have a significant impact on the antenna performance.

2 Structure of the Proposed Antenna System

A nonagon (9-sided polygon) fractal geometry is proposed and will be the cornerstone in constructing the fractal antennas of this work. It is generally known that the iterated function system (IFS) can be easily employed and repeated with many iterations to construct a fractal shape. This algorithm can be firstly applied to straight line and repeated several times at different scales to build the intended fractal geometry as illustrated in Fig. 1.

The affine transformation of the suggested nonagon fractal shape in the ω-plane is represented in Eq. (1):

$$\begin{aligned}
\omega &= [r\cos\theta,\ -r\sin\theta,\ r\sin\theta,\ r\cos\theta,\ e,\ f]\\
\omega 1 &= [1/3,\ 0,\ 0,\ 1/3,\ 0,\ 0]\\
\omega 2 &= [-0.255,\ -0.214,\ 0.214,\ -0.255,\ 0.33,\ 0]\\
\omega 3 &= [-0.057,\ -0.328,\ 0.328,\ -0.057,\ 0.083,\ 0.2]\\
\omega 4 &= [0.166,\ 0.288,\ -0.288,\ 0.166,\ 0.033,\ 0.53]\\
\omega 5 &= [0.313,\ 0.114,\ -0.114,\ 0.313,\ 0.2,\ 0.83]\\
\omega 6 &= [0.313,\ 0.114,\ -0.114,\ 0.313,\ 0.5,\ 0.9]\\
\omega 7 &= [0.166,\ 0.288,\ -0.288,\ 0.166,\ 0.8,\ 0.83]\\
\omega 8 &= [-0.057,\ -0.328,\ 0.328,\ -0.057,\ 0.966,\ 0.53]\\
\omega 9 &= [-0.255,\ -0.214,\ 0.214,\ -0.255,\ 0.91,\ 0.2].
\end{aligned} \tag{1}$$

Fractal loops were widely investigated as multiband antennas due to the self-similarity characteristics of fractal shapes. A fractal slot antenna based on a fractal loop geometry is designed in this work as a multiband candidate for RF energy harvesting applications. The geometry of the proposed fractal slot antenna is built based on the 2nd iteration of the proposed fractal nonagon as illustrated in Fig. 2. The dimensions of the designed antenna are shown in full details and it has been simulated by CST Studio Suite. A standard FR-4 substrate with $\varepsilon r = 4.1$, a thickness of 1.6 mm and a loss tangent (δ) of 0.02 was utilized.

It is clearly seen form Fig. 2 that the fractal slot has divided the geometry into two sections: the internal area of the loop and outer part that lies around the fractal slot loop. Thus, in the next step the internal area has been

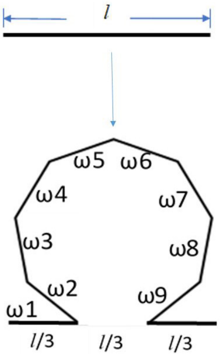


Fig. 1 The proposed fractal curves (first iteration).

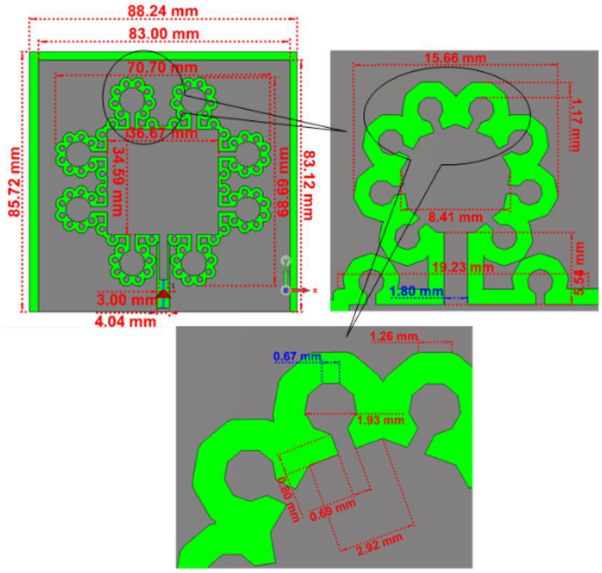


Fig. 2 Proposed fractal slot antenna based on 2nd of the proposed nonagon.

moved to the back of the substrate acting as a ground plane as shown in Fig. 3, where a complementary structure is yielded. This idea has been implemented in order to enhance the multiband performance of the antenna.

However, still there are several frequency bands at higher frequencies such as sub-6 GHz 5G bands not covered yet by this modification. Thus, another modification is proposed by keeping the internal area on the front side of the substrate but scaling it down to achieve higher frequency resonances with using the same antenna structure as illustrated in Fig. 4 and the return loss shown in Fig. 5 (curve No.3).

Now after applying the new modification it is noted that the lower frequency band has disappeared and the 2.2 GHz band has been shifted toward 2.5 GHz. In addition, it is seen that a wide resonance around 5 GHz appeared, which is preferable for 5G frequency bands. The achieved resonant frequencies can be easily played with and shifted to the left or right of the frequency spectrum to obtain a resonant frequency at the exact intended frequency. However, this is still not enough for the antenna to cover as many bands as possible as it is not easy for the current structure to add more resonant frequencies. Thus, another modification on the antenna structure is critically needed.

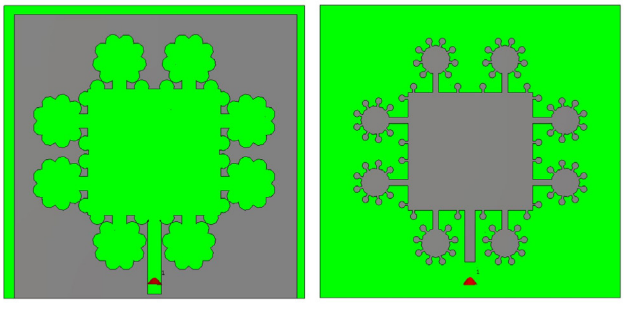

Front
Back

Fig. 3 Front and back sides of the proposed antenna after moving the internal area to the back of the substrate.

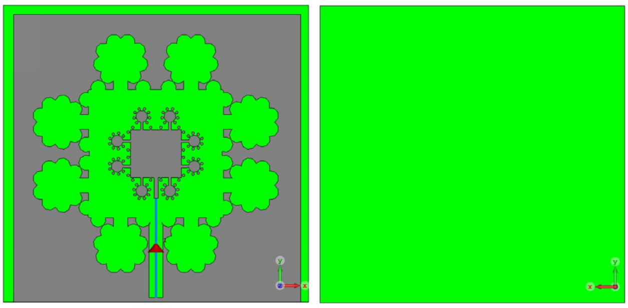

Front
Back

Fig. 4 The proposed fractal slot antenna with scaling down the internal area by 40%.

The return loss of the modified antenna is shown in Fig. 5 (curve No.2). It is obvious that the reflection characteristics have been significantly improved, particularly at 2.2 GHz and 3.5 GHz.

The simulated S-parameters of the fractal slot antenna is shown in Fig. 5 (curve No.1). It can be seen that the designed antenna exhibits multiband performance as expected. The antenna resonates at around 2 GHz, 2.2 GHz and 3.5 GHz. However, this performance is still not sufficient for energy harvesting application as there several important bands not covered by this antenna and even the resonance behavior is still weak at two frequencies (i.e. 2 GHz and 3.5 GHz), where the return loss didn't reach −10 dB.

3 Parametric analysis of the proposed antenna

The purpose of the parametric study is to find the structural and geometrical parameters of the proposed antenna that directly affect the antenna performance and also to find an optimized antenna structure that fits with the aim of this work. The main idea behind the parametric analysis is to identify the structural parameters that play a key role in shifting the resonance frequency left or right, improve the reflection characteristics and add new resonant frequencies. To this end, the parametric study includes scaling the antenna dimensions, playing with ground plane structure, and changing the length of the feeding inset.

3.1 Scaling the dimensions of the fractal structure

One of the easiest ways to shift the resonant frequency left or right is to scale the antenna size up or down in order to adjust the resonance at the desired value. Thus, in this

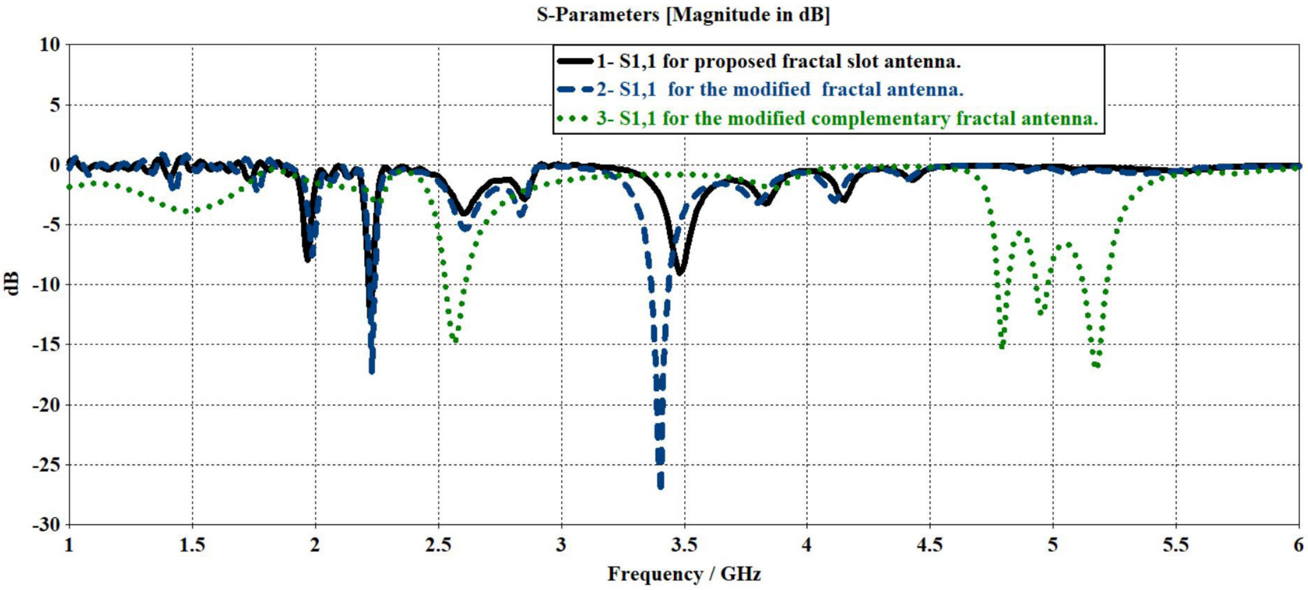


Fig. 5 Simulated return loss (S11) for the proposed fractal antenna with all of its modifications.

step the antenna dimensions were scaled up and down and the impact of changing the size on the S-parameters was observed. Fig. 6 shows the variation return loss versus frequency at several scaling ratios. It can be clearly noticed how the antenna resonates for each case. The shift in resonant frequencies of the antenna is clearly observed in Fig. 6 for the whole frequency band of interest with better improvement at lower frequencies.

3.2 The impact of the ground plane

In Subsection 3.2, the proposed fractal slot antenna has undergone more modification to add more resonant frequencies in order to be able to cover additional communication systems. To this end, a partial ground plane is added to the back of the substrate which is expected to enhance the antenna reflection performance and contribute towards the addition of new frequency bands. The backside of the proposed fractal slot antenna is illustrated in Fig. 7 showing the designed ground plane with different geometrical modifications; and the simulated return loss is shown in Fig. 8. It is worth mentioning that a few modification is also applied to the feeding of the antenna.

As demonstrated in Fig. 6, the final structure of the proposed fractal slot antenna is exhibiting a multiband resonance at several frequency bands. The simulation results showed that several resonant frequencies have been obtained, where most of them have a good reflection properties with a return loss of more than 10 dB. The addition of the partial ground plane has significantly influenced the antenna performance, where the reflection properties were clearly improved and numerous resonant frequencies appeared within the range from 1 GHz to 6 GHz. The

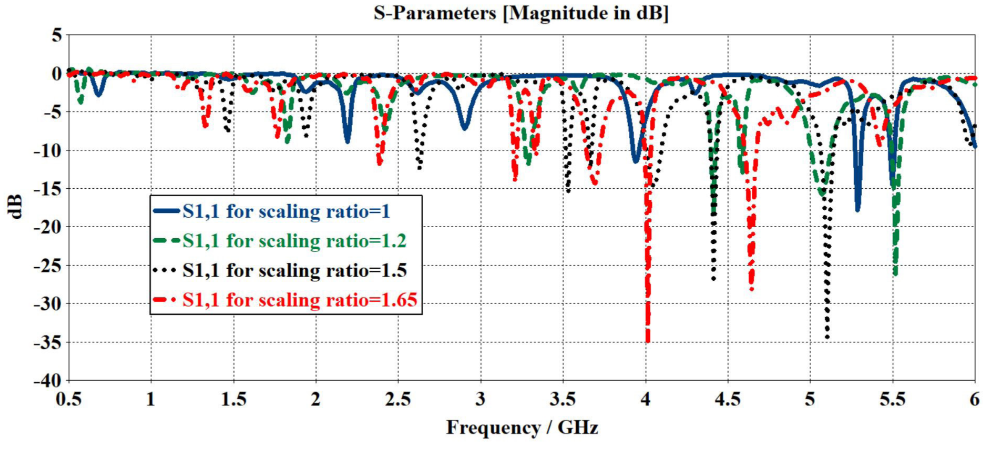
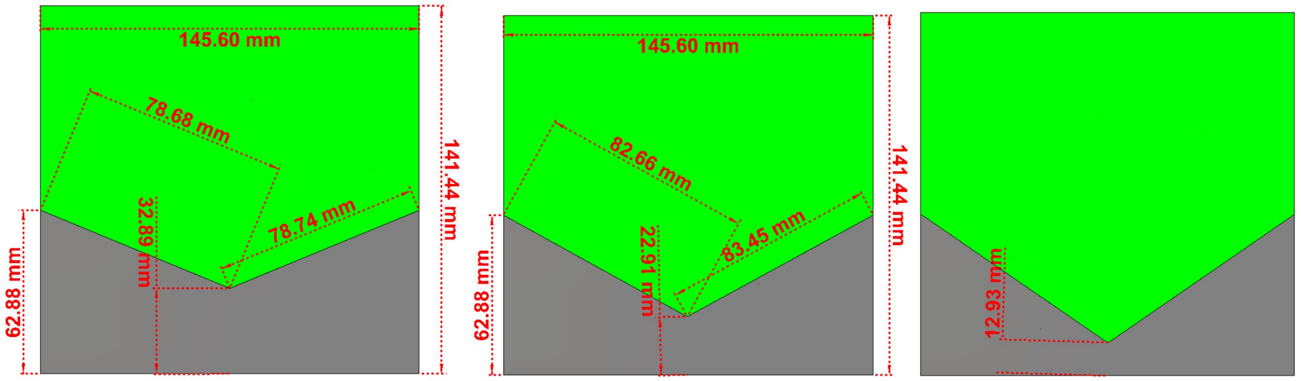


Fig. 6 Simulated return loss (S11) for the modified fractal antenna with changing the antenna size.



Shift in vertex distance = +10 mm Shift in vertex distance = 0 mm Shift in vertex distance = -10

Fig. 7 The proposed partial ground plane of the fractal slot antenna showing three cases of the vertex position.

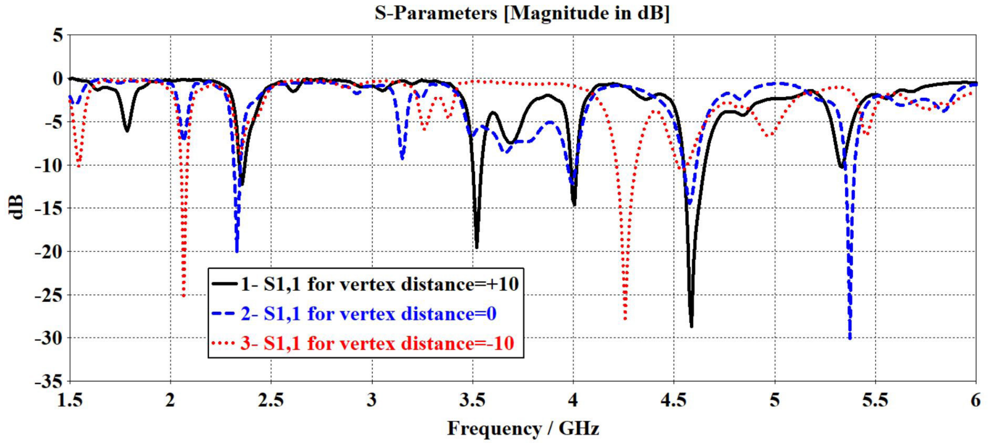


Fig. 8 Simulated return loss (S11) for the modified fractal antenna with changing the location of the ground plane's vertex.

antenna with its current status covers many of the GSM, LTE, UMTS and 5G frequency bands, which is highly requested for the RF energy harvesting applications. All what is needed now is to find the geometrical details that have a direct impact on the antenna performance in order to adjust and fine tune the resonant frequencies to make them compatible with the current active communication systems.

The impact of the ground plane shape on the performance has been studied. Firstly, the ground plane shape is slightly modified by moving the shape's vertex up and down by 10 mm and the effect of this move is numerically studied. Fig. 7 showed the three cases of the ground plane, whereas Fig. 8 shows the return loss of the antenna for the three aforementioned cases.

As noticed from Fig. 8, moving the location of the ground plane's vertex has clearly demonstrated the direct impact on the antenna performance. This gives the designer the freedom of shifting the resonant frequency and adds more control on the antenna overall performance by selecting the optimum locations that leads to the desired performance.

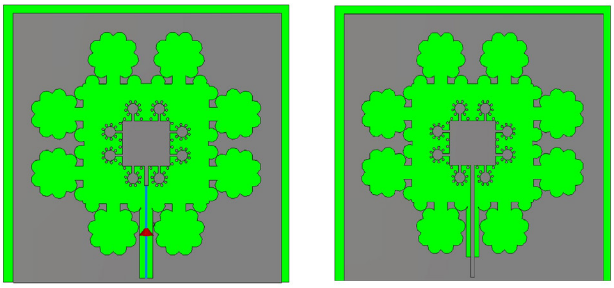
3.3 Changing the length of the feeding inset

Another structural parameter was studied in this work, which is the feeding length as illustrated in Fig. 9. The length value was varied from 0 mm to 30 mm from the edge of the substrate by a step of 10 mm. The effect of this change on the antenna performance is depicted in Fig. 10.

Fig. 10 clearly shows that changing the feeding inset length affects only the lower frequencies in particular between 2 GHz and 4 GHz with a trivial impact on higher frequencies. This parameter can be effectively used to control the resonance at the lower band frequencies by shifting the resonant frequency value and/or improve the reflection characteristics.

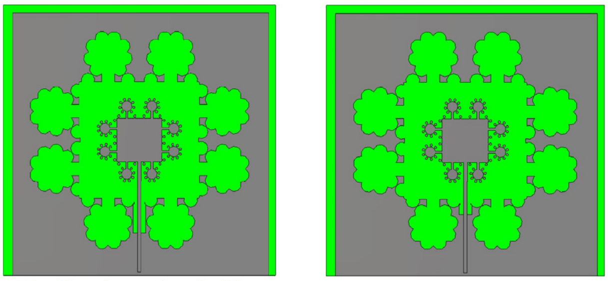
4 Optimized fractal loop antenna

From the parametric study in Section 3 and the results analysis, an optimized antenna structure is determined. The selection was based on the antenna performance that have resonant frequencies aligned with the ambient RF sources. The final antenna parameters extracted from the parametric



Feeding inset depth=0 mm (i.e at origin)

Feeding inset depth=10 mm



Feeding inset depth=20 mm

Feeding inset depth=30 mm

Fig. 9 The modified fractal antenna with changing feeding inset length.

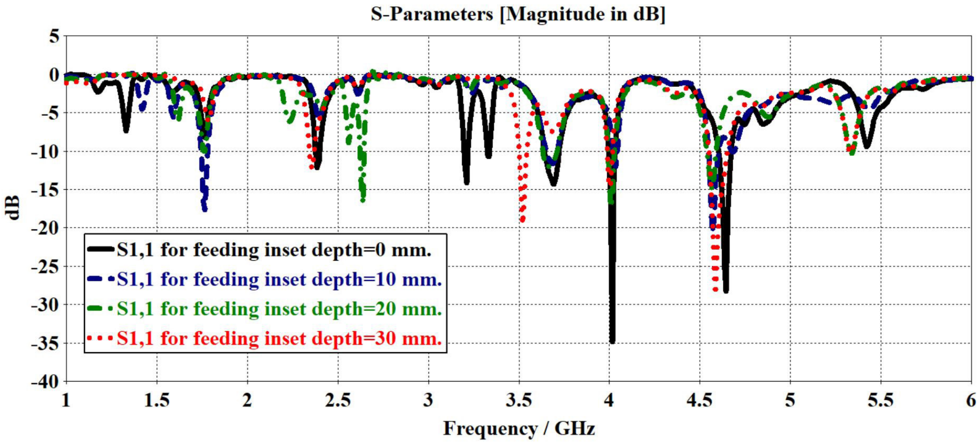


Fig. 10 Simulated return loss (S11) for the modified fractal antenna with changing feeding inset length.

study of this work were a 1.65 scaling ratio, a ground plane vertex that lies 32.89 mm away from the substrate edge and a feeding inset 30 mm away from the edge were selected.

It can be seen that the optimized antenna has seven resonant frequencies at 1.8 GHz, 2.4 GHz, 3.45 GHz, 3.6 GHz, 4 GHz, 4.6 GHz and 5.3 GHz covering several ambient communication networks (GSM, UMTS and 5G), Bluetooth and WLAN systems. The current results make this antenna a good candidate for RF energy harvesting applications. However, one last attempt was tried in this work to find other structural parameters that can improve the performance or re-locate some of the resonant frequencies. The aim is to find all the geometrical parameters that play a key role in improving the antenna performance, which gives the designer more degree of freedoms. The mentioned attempt was changing the shape of the ground plane arbitrary and then optimize it to achieve the desired performance. The shape of the new ground plane is illustrated in Fig. 11 and the return loss of the new antenna compared with the optimized antenna is depicted in Fig. 12. It is worth mentioning that the shape of the ground planes in this work was chosen arbitrarily and it was geometrically optimized to enhance the bandwidth and adjust the position of the resonant frequencies.

A close look at Fig. 12 reveals that changing the ground has shifted some of the resonant frequencies, improved

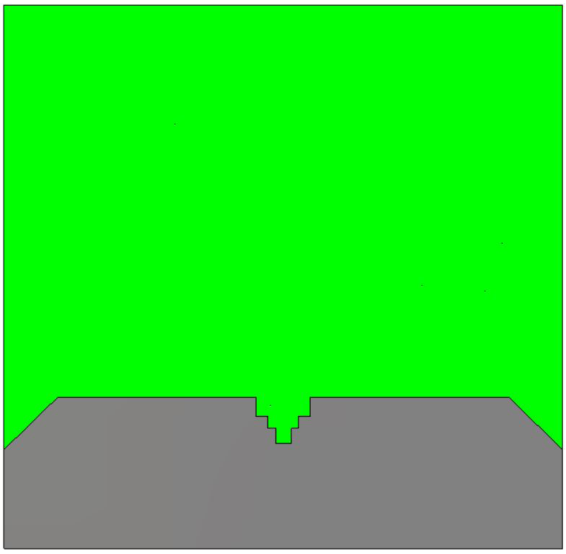


Fig. 11 The proposed modification on the ground plane of the fractal slot antenna.

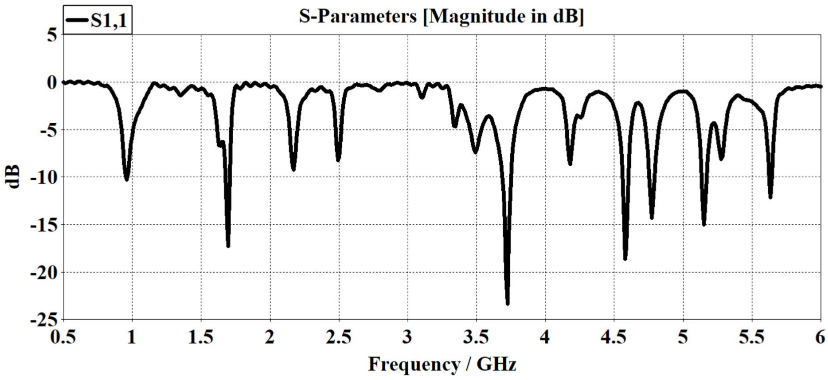


Fig. 12 Simulated return loss (S11) for the optimized fractal slot antenna with the new ground plane (Antenna 2).

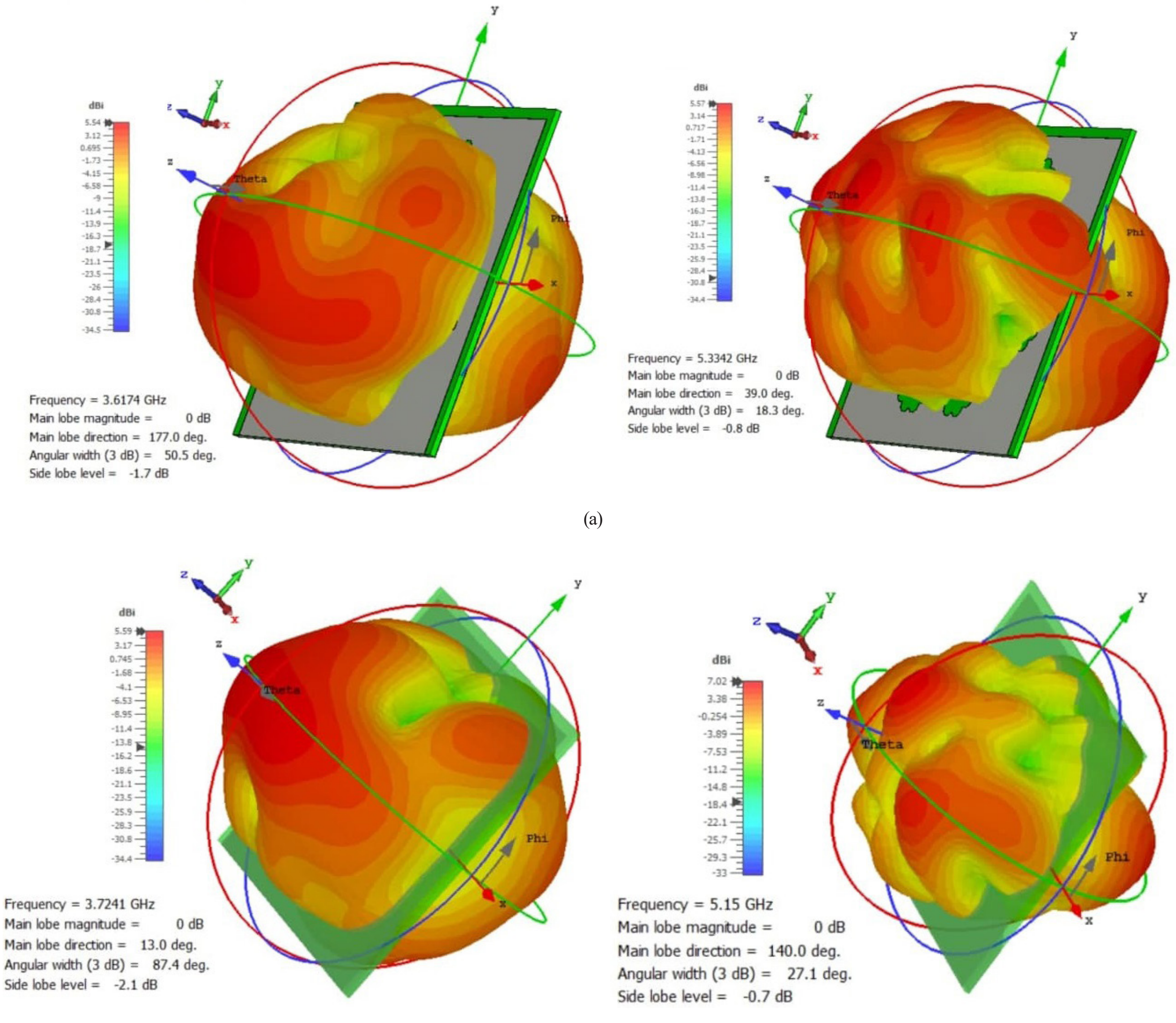
some them and created new resonances. The lower frequency band has been shifted to left slightly but it is significantly improved to reach beyond −10 dB. On the other hand, a new resonances were appeared at 3.7 GHz, 4.6 GHz, 5.2 GHz and 5.65 GHz, where all of them lie within the 5G communication systems.

The parametric study and analysis implemented in this work has yielded two antenna structures as final designs. The first one is the optimized antenna structure with arbitrary shape ground plane (will be named Antenna 1 throughout the rest of this paper) and the second antenna with the modified arbitrary ground plane shown in Fig. 11 (will be named Antenna 2). Both Antenna 1 and Antenna 2 have shown excellent resonance behavior and can be effectively employed in RF energy harvesting systems. As it was mentioned earlier in this paper it is important for the antenna to be matched with reference impedance of the rectifier circuit and must have good radiation efficiency and high gain. The radiation pattern of both antennas at selected resonant frequencies are shown in Fig. 13.

Fig. 13 shows that both antennas have almost omnidirectional performance, which is preferable feature in this application with some unavoidable nulls at certain angles. Tables 1 and 2 summarize the important frequency and radiation parameters such as gain, efficiency and frequency bandwidth at different frequencies for both Antenna 1 and Antenna 2, respectively.

5 Experimental results

The two proposed antennas (i.e. Antenna 1 and Antenna 2) were fabricated and their return loss and radiation pattern were measured in the lab. Both antennas have identical front side, however, they have different ground planes. It is already demonstrated throughout the simulations



(b)

Fig. 13 Simulated 2D and 3D radiation pattern for Antenna 1 and Antenna 2 at selected frequency bands; (a) Antenna 1 @ 3.6 and 5.3 GHz; (b) Antenna 2 @ 3.7 and 5.15 GHz

Table 1 Gain, efficiency and bandwidth of Antenna 1 at different frequency bands.

	Gain (dBi)	Efficiency	Bandwidth (MHz)
@ 1.7 GHz	4.51	87%	3.0
@ 2.45 GHz	5.76	92%	53.4
@ 3.6 GHz	5.54	95%	48.6
@ 5.33 GHz	5.56	89%	98.6

Table 2 Gain, efficiency and bandwidth of Antenna 2 at different frequency bands.

	Gain (dBi)	Efficiency	Bandwidth (MHz)
@ 0.95 GHz	3	97%	10.9
@ 1.7 GHz	5.21	80%	28.2
@ 2.49 GHz	3.19	91%	N/A
@ 3.5 GHz	6.7	93%	63.2
@ 4.5 GHz	7.3	87%	41.8
@ 5.15 GHz	7.01	85%	35.8

that the ground plane plays a crucial role in relocating the resonant frequencies and could add additional ones. Fig. 14 illustrates photographs of the fabricated antennas. A fully anechoic chamber is unfortunately not available in the department where the measurements were taken, thus a testing arrangement was organized using absorbing material to form a semi-anechoic chamber to measure the return loss and the radiation pattern experimentally as shown in Fig. 14. Fig. 15 compares the measured and simulated return loss of both antennas within

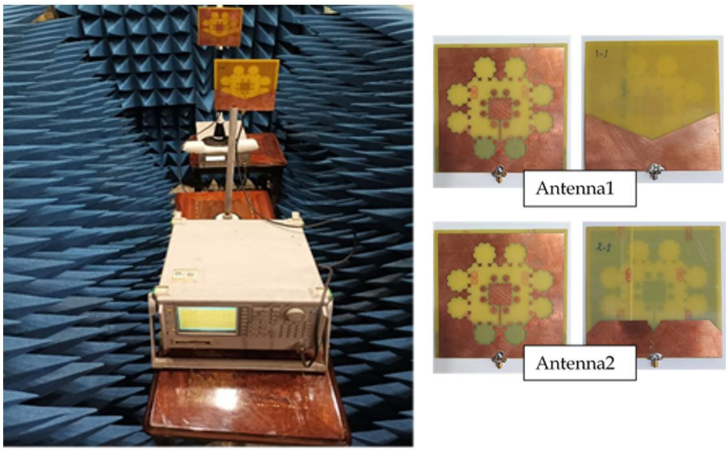
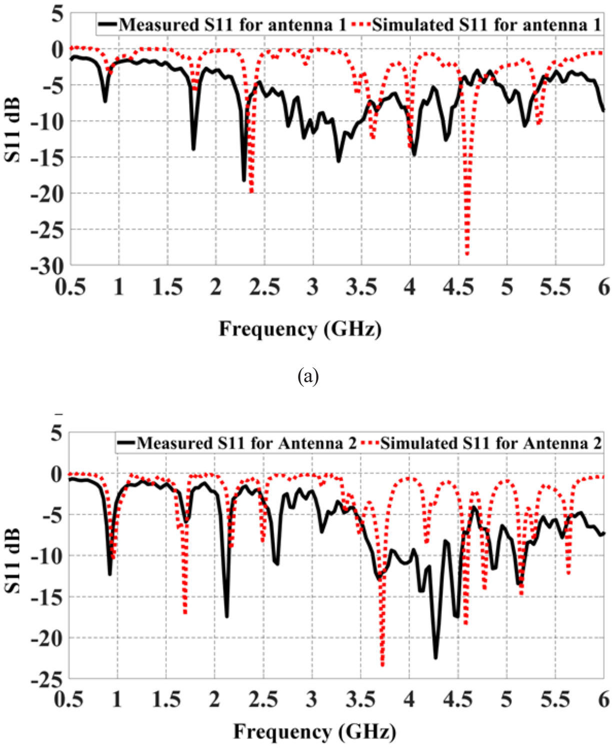


Fig. 14 Photograph of the front and back sides of the fabricated antennas and the experimental measurement setup.



(a)

(b)

Fig. 15 Measured return loss (S11) compared to the simulated one for the fabricated fractal slot antennas; (a) Antenna 1; and (b) Antenna2.

the frequency range 0.5–6 GHz. It can be seen that there is a good agreement between the simulated and measured reflection characteristics of both antennas, where both of them have exhibited multiband performance experimentally and hit the targeted bands of interest. The number of resonant frequencies that went beyond −10 dB are promising. On the other hand, the measured radiation pattern of both antennas at certain frequencies compared with simulated one is shown in Fig. 16. The selected frequencies are 3.26 GHz and 5.18 GHz for Antenna 1; and 3.68 GHz and 5.12 GHz for Antenna 2. It is noticed that the measured pattern is somehow resembles the simulated one with a rotated view. The agreement between the simulation and measurements was quite good at lower frequencies and the differences at higher frequencies is reasonable due to the imperfect testing environment, but it is still acceptable and proofs the concept of this paper. The differences can be justified to the imperfect testing environment and

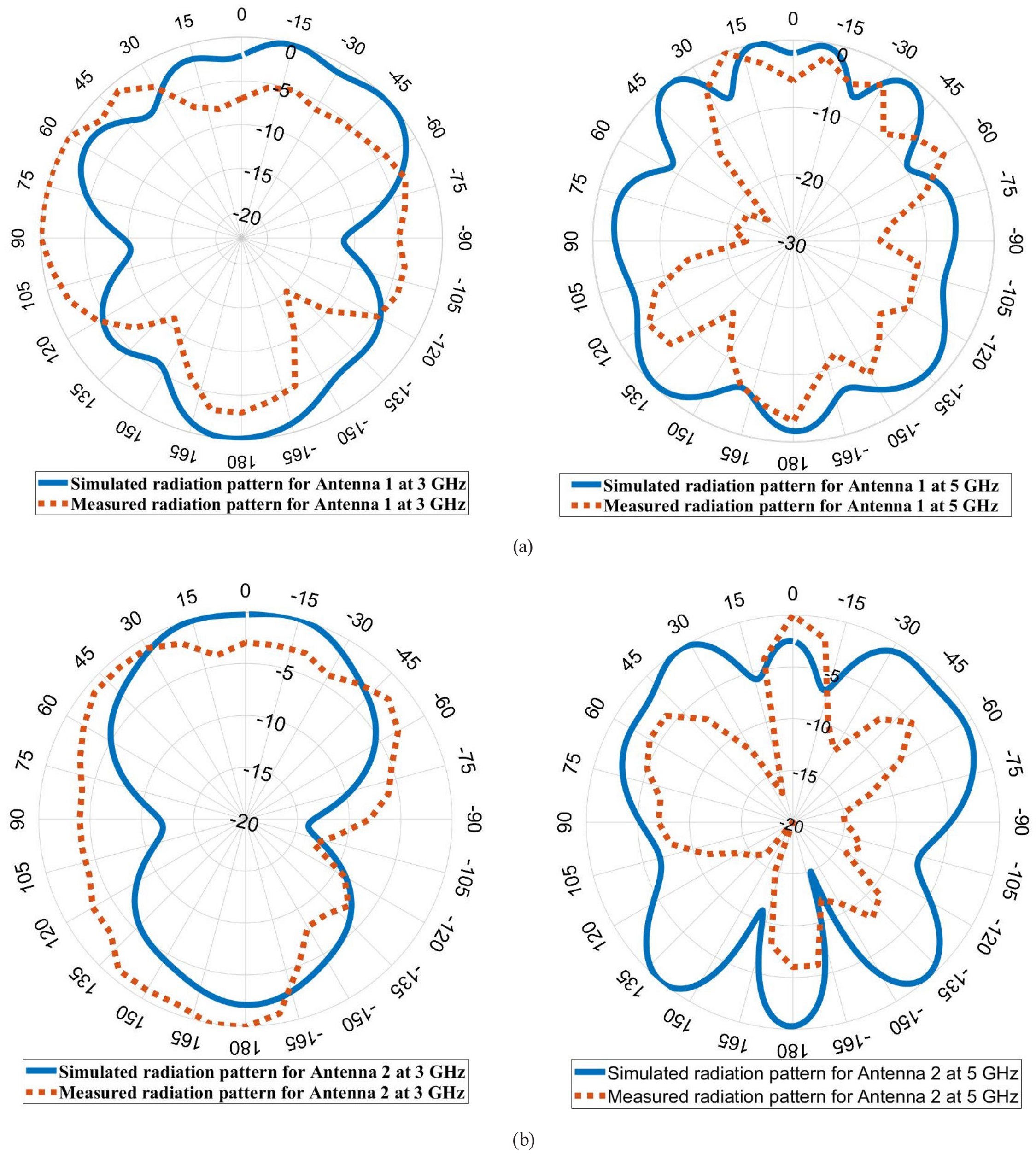


Fig. 16 Measured and simulated 2D radiation pattern for the proposed fractal slot antennas: (a) Antenna 1 at 3.26 GHz & 5.18 GHz; and (b) Antenna 2 at 3.68 GHz & 5.12 GHz.

can be better improved by utilizing a full anechoic chamber. In addition, it is known that fractal shapes contain many fine details, sharp angles and numerous corners, which are not easy to be fabricated using chemical etching PCB technique. Since the antenna has large slot with many corners and edges that perturb the current flow forcing the current to flow around the curvature of the slot. Thus, any geometrical differences between the simulated and fabricated structures would severely affect the radiation pattern especially at higher frequencies due to the differences in the very fine details of the structure. It is worth mentioning here that the aim of this paper is to introduce a step by step procedure in designing and optimizing multiband fractal slot antennas for RF energy harvesting applications and how to make the antenna resonance is aligned with the targeted ambient RF systems. The introduced procedure can also be applied in the design of multiband fractal slot antennas for mobile communication systems such the future 5G networks and other wireless communication systems.

6 Conclusion

In this paper, a step by step procedure of the design and optimization of multiband fractal slot antennas for RF energy harvesting applications is presented. Two fractal slot antennas based on the 2nd iteration of a proposed fractal geometry were designed, optimized and implemented. The design process started with a proposed fractal slot based on a fractal loop. The process has then been developed by scaling down the internal area to achieve multiband performance and improve the reflection characteristics at all resonant frequencies. A parametric study is then followed to better enhance the antenna performance and adding more resonant frequencies at the specific bands of interest. The parametric study has shown that scaling the dimensions of the fractal slot would make the antenna exhibit multiband performance at high frequencies targeting the 5G mobile systems. The final antenna parameters extracted from the parametric study of this work were a 1.65 scaling ratio, a ground plane vertex that lies 32.89 mm away from the substrate edge and a feeding inset 30 mm away from the edge. In addition, it is found that perturbing the shape of the ground plane has a significant impact on the antenna performance. It is found that the ground plane has a significant impact on the performance of the proposed antennas. However, it is main influence was on the bandwidth and shifting the resonant frequency. On the other hand, it has been proved throughout Figs. 5 and 6 that the fractal shape plays a key role in adding or shifting the frequency bands due to the self-similarity property of fractal geometries. From the simulation analysis, two fractal slot antennas were optimized to resonate at several bands within the frequency range from 0.5 GHz to 6 GHz. The optimized antenna has seven resonant frequencies at 1.8 GHz, 2.4 GHz, 3.45 GHz, 3.6 GHz, 4 GHz, 4.6 GHz and 5.3 GHz covering several ambient communication networks (GSM, UMTS and 5G), Bluetooth and WLAN systems. Simulation results shows that Antenna 1 has achieved a gain of more than 4.5 dBi at all the resonant frequencies with a radiation efficiency ranged between 87%–95%; whereas Antenna 2 has achieved more than 3 dBi gain at lower frequencies while reaching around 7 dBi at higher frequencies with a radiation efficiency ranged between 80%–97%. Simulation results have also shown that both optimized antennas are good candidates for this application covering many ambient RF sources and they both have acceptable radiation pattern that fits well within the aim of this work. Finally, the optimized antennas were fabricated and their performance were tested in the lab. Experimental results showed that there is acceptable agreement between simulation and measurement results taking into account the unavoidable errors that come from the fabrication difficulties imposed by the fine detail of fractal geometries and the imperfect testing environment. It is believed that this paper introduce a good designing guidelines for those who are interested in exploring the feasibility of fractal antennas for the RF energy harvesting application.

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