Fabrication and Performance Evaluation of a Fractal-based Slot Printed Antenna for Dual-band Wireless Applications

Seevan F. Abdulkareem, Jawad K. Ali, Ali I. Hammoodi. Ali J. Salim,

Mahmood T. Yassen and Mohammed R. Hussan

Microwave Research Group, Department of Electrical Engineering, University of Technology, Iraq

email: eng_seevan85@yahoo.com

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Abstract – Different fractal geometries are successfully applied to design compact size printed and microstrip antenna structures for multiband and dual-band wireless communication applications. In this paper, a printed antenna with fractal based slot structure is presented as a candidate for use in dual-band wireless applications. The slot structure of the proposed antenna is with circle based fractal geometry. The slot structure has been etched in the ground plane of an FR4 substrate with relative dielectric constant of 4.4 and 1.6 mm thickness and on the reverse side a microstrip line has to be printed as a 50 Ω feed. Simulation results of the modeled antenna show that it offers a dual-band resonant behavior with a considerable resonant frequency ratio; covering a wide variety of wireless applications. Modeling and performance evaluation of the resulting antenna are carried out using the commercially available EM simulator HFSS, from Ansoft Corporation. A parametric study reveals that the proposed antenna offers fractional bandwidths of about 13% to 27% for the lower resonant band and 7% to 28% for the upper resonant band. The corresponding gain throughout these bands varies from 2.53 to 3.58 dB and from 4.08 to 5.76 dB respectively. This makes the antenna suitable for use in a wide variety of wireless applications. A fabricated prototype of the proposed antenna shows a return loss response which is in reasonable agreement with that theoretically predicted within the same swept frequency range. Furthermore, the proposed antenna exhibits good radiation characteristics at the resonant bands.

Keywords – Fractal antenna; slot antenna; dual-band antenna; printed antenna; circle-based fractal geometry.

1. Introduction

Nowadays, many communication services, such as PCS, WiBro, WiMAX, and wireless LAN, have recently become available below 6 GHz frequency range. Mmultiple frequencies have been allocated for the development of high-speed mobile information and communication systems in this frequency range. This has triggered the researchers to design compact and multiband antennas that can transmit and receive with more than one frequency signal [1].

In this respect, microstrip and printed antennas are promising candidates for this design due to their low profile, low-weight, and ease of fabrication [2]. Beside these features, microstrip antennas suffer from their narrow bandwidths. To overcome this drawback, slot structures with different shapes, such as C-shape, E-shape, T-shape and U-shape, have been employed to design broadband wideband printed antennas [3-7].

On the other hand, various fractal geometries have found their way in the antenna design in order to produce compact and multiband antennas benefiting from their unique properties; space filling and self similarity respectively. Conventional fractal geometries such as Koch, Cantor, Hilbert, Sierpinski, Minkowski and other fractal curves have been successfully used to design dual-band and multiband printed slot antennas for various wireless applications [8-17].

It is worth to note that the employment of fractal geometries in the design of slot printed antennas for dual-band communication applications can be classified into two categories. In the first category, direct application of fractal geometries has been adopted [8-12]. In this case, the fractal geometries constitute the whole antenna slot structures. The slot antennas designed according to this category offer dual-band resonant responses without the need of any type of tuning elements. However, in the second category, the antenna slot structure is a combination of Euclidian geometries, such as triangle, square, rectangle and any other polygons, and fractal geometries superimposed on these structures, where each line segment is replaced by fractal curve with certain iteration level [13-17]. In this case, the multiband behavior has been reached in different techniques. These include the addition of tuning stubs to the feed line, modification of the slot structures or by rotating it around the antenna axis. Recently, printed slot antennas with fractal slot structures based on circular shapes have been reported to be successfully used in the design of antennas with dual-band and multiband characteristics [18-21].

In this paper, a printed fractal slot antenna has been presented as a candidate for use in dual-band wireless applications. The slot structure of the proposed antenna is obtained by the direct application of circle based fractal geometry on the antenna ground plane. The antenna has been fed with a 50 Ω microstrip line etched on the reverse side of the substrate. A fabricated prototype of the proposed antenna shows a return loss response which is in reasonable agreement with that theoretically predicted within the same swept frequency range.

2. The Proposed Antenna Structure

The proposed antenna slot structure has been essentially extracted from the basic structure of the well-known Figure of Life shown in Fig. 1(a) [22-23]. After the omission of the upper and the lower two circles, the resulting structure, Fig. 1(b), then represents the first iteration of the proposed fractal based slot structure.

Higher iterations could be obtained by drawing two asymptotic circles inside each internal circle, and the process is to be repeated in the subsequent iteration levels. Figures 1(c) and 1(d) demonstrate the generation process for the second and the third iterations respectively.

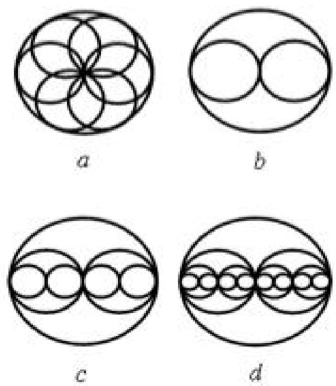

Figure 1. The steps of growth of the proposed fractal structure: (a) The basic Figure of Life structure, (b) to (d). The subsequent iterations corresponding to the 1st up to the 3rd levels.

This fractal geometry has a simple structure. It is predominantly composed of circles with different scales. This will consequently lead to an easy to fabricate printed antenna structure for dual-band application. As compared with antenna structures reported in [10, 11, 24-27], the proposed antenna structure will be with the simplest structure.

3. The Antenna Design

A printed fractal based slot antenna, with the slot structure depicted in Fig. 1(c), has been initially designed with an external circle diameter of 45 mm and square ground plane dimensions of 50 mm × 50 mm. The slot structure is supposed to be etched on the ground plane of an FR4 substrate with relative dielectric constant of ε_r =4.4 and thickness of 1.6 mm. On the reverse side of the substrate, the antenna is fed by a 50 Ω microstrip line of length 20 mm and width 3.05 mm width, symmetrically centered beneath the slot structure. The layout of the modeled antenna with respect to the coordinate system is depicted in Fig. 2. Table 1 summarizes the dimension of the modeled antenna.

The antenna with the dimensions depicted in Table 1, has been found to possess a dual-band resonant behavior within the swept frequency range of 1–7 GHz with a lower resonant frequency at 1.88 GHz.

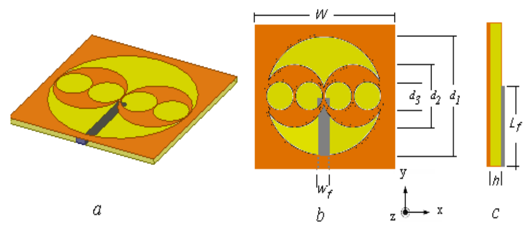

Figure 2. The layout of the modeled antenna with respect to the coordinate system: (a) The 3D view, (b) The front view, and (c) The side view.

Table 1. Summary of the antenna dimensions

Parameter	Value (mm)	Parameter	Value (mm)
d_1	45.00	W	50.00
d_2	22.50	w_f	3.05
d_3	11.25	L_f	20.00

Observing the influence of the various parameters on the antenna performance, it has been found that the dominant factor in the antenna is the external slot diameter d_1 in terms of the guided wavelength λ_g:

$$\lambda_g = \frac{\lambda_\circ}{\sqrt{\varepsilon_{eff}}} \quad (1)$$

where ε_{eff} is the substrate effective dielectric constant. The majority of the recently available EM simulators provide direct computation of both λ_g and ε_{eff} at a certain frequency for given substrate parameters. In terms of the external circle diameter d_1 and the guided wavelength λ_g, the lower resonant frequency, f_1, is given by:

$$f_1 = \frac{c}{2d_1\sqrt{\varepsilon_{eff}}} \tag{2}$$

where c is the speed of light in free space.

4. Performance Evaluation

The antenna, with the layout depicted in Fig. 2, has been modeled with prescribed substrate, and numerical analysis of its performance is carried out using the commercially available EM simulator HFSS, from Ansoft Corporation [24]. Simulation results reveal that the antenna offers a dual-band response within the sweep frequency of 1-7 GHz. This does not prevent the possibility of the existence of other resonances outside this frequency range.

A parametric study of the effect of the feed line length on the antenna return loss response is demonstrated in Fig. 3. The results imply that, as the feed line extends towards the center of the slot structure; both of the resonant bands are shifted to the left with increasing resonant frequency ratio f_2/f_1. The variation of the resonant frequency ratio f_2/f_1 versus the feed line length is presented in Fig.4.

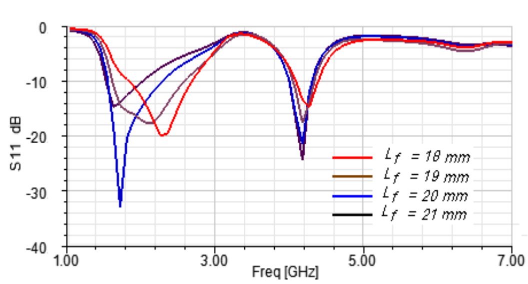

Figure 3. Simulated return loss responses of the modeled antenna with the feed line length as a paramerer.

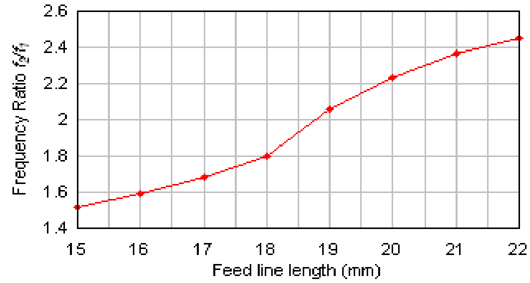

Figure 4. The variation of the frequency ratio f_2/f_1 as a result of increasing the antenna feed line length.

Table 2. Antenna fractional bandwidths and gains

Feed Line Length (mm)	Resulting Parameters			
	FBW_1 (%)	FBW_2 (%)	G_1 (dB)	G_2 (dB)
15	13.01	28.40	3.58	5.73
16	19.78	6.65	3.58	4.08
17	24.70	7.22	2.90	5.8
18	27.50	7.27	2.53	5.76

Furthermore, the results imply that the variation of the feed line length has more impact on the position of the lower resonant band in comparison with that of the upper resonant band where its position is slightly shifted down within the swept frequency.

In addition, the ratio of the upper and the lower resonant frequencies, f_2/f_1, has varied with a considerable range from about 1.5 to 2.45 as shown in Fig.4 corresponding to feed line change from 15 to 22 mm. This makes the proposed antenna a suitable candidate for use in a wide variety of communication services.

Furthermore, the variation of the antenna feed line length has its impact on the antenna fractional bandwidths FBW_1 and FBW_2 and their corresponding antenna gains G_1 and G_2. Table 2 demonstrates the details of these parameters. Shorter lengths of the feed line result in narrower FBW_1 and wider FBW_2, but with higher values of both G_1 and G_2. However, G_1 is less than G_2 for all values of the feed line, while FBW_1 is generally wider than FBW_2. This is of significant importance since most of the modern communication services operate in the lower band.

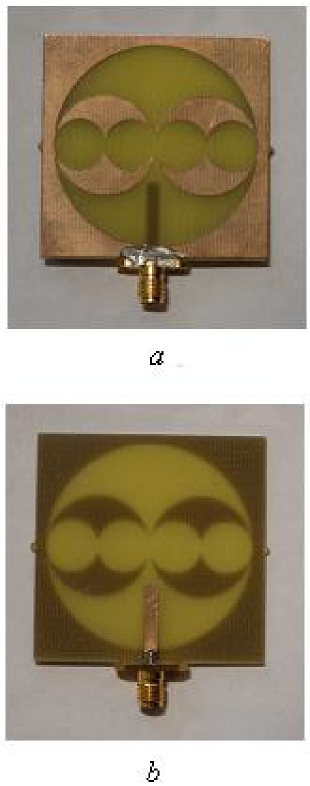

Figure 5. Photo of the fabricated antenna prototype: (a). Top view, and (b). Bottom view.

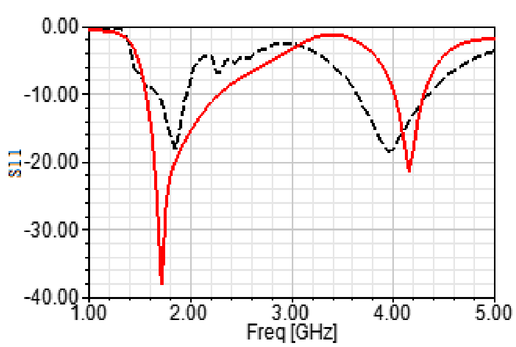

Figure 6. Measured (dotted black) and simulated (continous red) return loss responses of the proposed antenna.

A prototype of the proposed antenna has been fabricated using an FR4 substrate with dielectric constant of 4.4 and 1.6 mm thickness. Figure 5 demonstrates a photo of this antenna prototype. Measured and simulated return loss responses of the proposed antenna are shown in Fig. 6. As it is implied in this figure, measured results for the lower resonant band approaches those theoretically predicted, while there is a slight difference for the upper resonant band. This might be attributed to the fabrication tolerances in the production process of the prototype. Consequently, the differences at the upper resonant band are larger since this band is attributed by the smallest parts constituting the slot structure.

The far field radiation pattern characteristics of proposed circle based fractal slot antenna, for feed line length of 18 mm, have been numerically calculated as shown in Fig. 7. In this case, the proposed antenna resonates at 2.45 GHz and 4.20 GHz in broad side direction at $\varphi=0°$ and $\varphi=90°$.

The results show monopole like radiation patterns with omnidirectional radiation. However, the radiation patterns depicted in Fig. 7(a) corresponding to first resonance are very close to those of monopole radiator, while the radiation patterns corresponding to the second resonance are slightly different as shown in Fig. 7(b).

The investigation of the EM characteristics of the radiation behavior of the proposed antenna is important to get more insight. The current distributions generated in the antenna have been simulated at 2.45 and 4.20 GHz, as shown in Fig. 8. It is worth to note that the same color scale has been adopted for the simulated current distributions for these frequencies. The results in Fig.8 (a) imply that a larger surface current distribution has taken place at 2.45 GHz resonance, and thus providing larger path for the current to flow producing lower resonance. However, as shown in Fig. 8(b), only a smaller surface current distribution occurs at 4.2 GHz providing a shorter path for the current to flow and leading to the creation of the upper resonance.

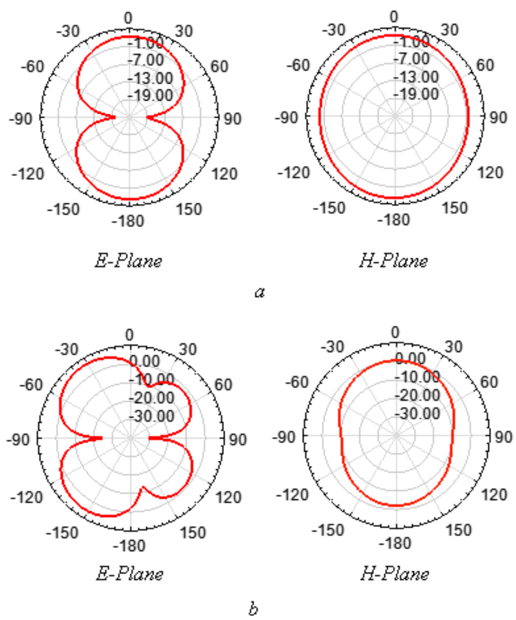

Figure 7. Simulated far field radiation patterns of the proposed antenna at (a). 2.45 GHz and (b). 4.20 GHz.

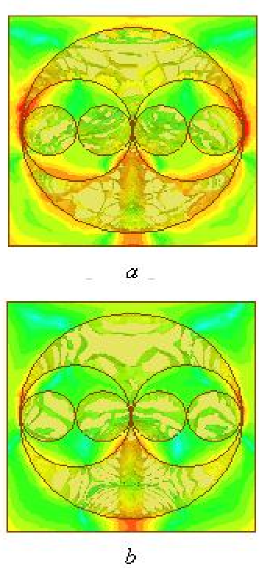

Figure 8. Simulated current distributions on the surface of the modeled antenna at: (a). 2.45 GHz and (b). 4.20 GHz.

Figure 9 shows the 3D field patterns at the two resonant frequencies; 2.45 and 4.20 GHz. Again, it has been found that the proposed antenna offers monopole like radiation patterns with approximate omnidirectional characteristics. The radiation patterns depicted in Fig. 9(a) corresponding to first resonance are very close to those of monopole radiator, while the radiation patterns corresponding to the second resonance are slightly different as shown in Fig. 9(b).

The antenna gain responses throughout the two resonant bands are shown in Fig. 10. The gain response throughout the first resonant band shows a variation of gain from about 1.85 to 2.35 dB with a maximum value of 2.4 dB, while the gain throughout the second resonant band varies between 5.48 and 5.75 dB with a maximum value of 6.15 dB. These values meet the gain requirements of most of the recently available communication services operating below 6 GHz.

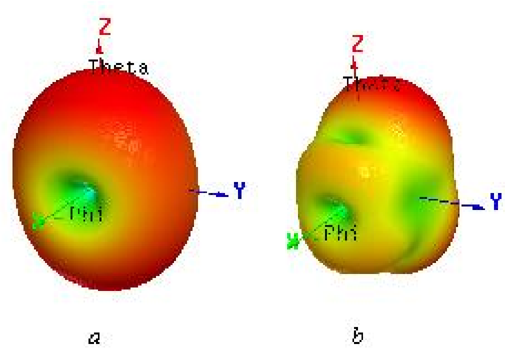

Figure 9. Simulated 3D electric field radiation patterns of the modeled antenna at: (a). 2.45 GHz and (b). 4.20 GHz.

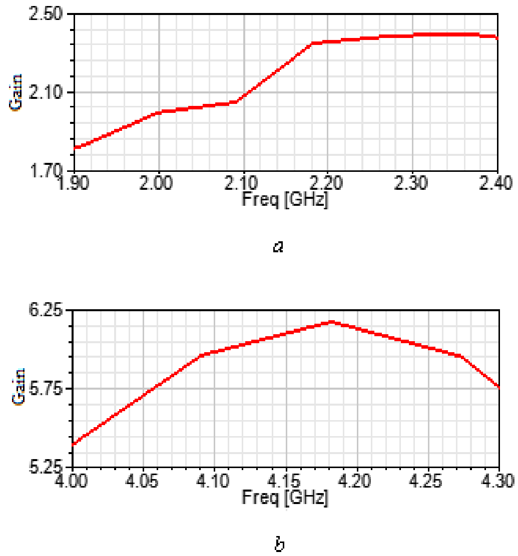

Figure 10. Simulated gain responses of the modeled antenna at: (a). 2.45 GHz and (b). 4.20 GHz.

5. Conclusion

In this paper, a new fractal based printed slot antenna has been presented as a candidate for use in dual-band communication applications. Parametric study has been carried out to demonstrate the effect of varying the feed line length beneath the antenna slot structure on the resulting performance. Performance evaluation results have shown that different feed line lengths lead to different antenna return loss responses with varying positions of the resonant bands and different ratios of the upper and lower resonant frequencies.

Furthermore, for the different feed line lengths, the antenna offers a dual-band resonant behavior with enhanced bandwidths and reasonable radiation characteristics and gain. This makes the proposed antenna suitable for a wide variety of dual-band wireless applications. Measured results of the return loss response of the proposed antenna have been found to be in reasonable agreement with that theoretically computed.

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