A New Fractal Multiband Microstrip Patch Antenna Design for Wireless Applications

Jawad K. Ali, Department of Electrical Engineering, University of Technology, Iraq
A New Fractal Multiband Microstrip Patch Antenna Design for Wireless Applications

Jawad K. Ali

Department of Electrical and Electronic Engineering,
University of Technology, P.O. Box 35239, Baghdad, Iraq

Email: jawengin@yahoo.com

Abstract

In this paper, a new compact, low profile multiband patch microstrip antenna design is presented as a candidate for use in modern multi-functions communication systems. The proposed antenna design is fractally generated using Koch fractal curve geometry applied to the conventional square microstrip patch antenna. Antenna structures resulting from the successive iterations in the proposed fractal generation process show a considerable size reduction compared with the conventional microstrip patch antenna designed at the same frequency using the same substrate material specifications. Simulation and theoretical performance of the resulting antenna structures corresponding to the different fractal iteration levels have been carried out using method of moments (MoM) based software package IE3D, which is widely used in the fields of microwave research and industry. Simulation results have proved the multi-resonant behavior of the presented antenna structures besides the considerable size reduction gained. The results also show that these antenna structures possess adequate radiation performance.

Keywords: Microstrip patch antenna, antenna miniaturization, fractal antenna, multiband antenna, Koch fractal curve geometry, L-probe feed.
INTRODUCTION

The term fractal, which means broken or irregular fragments, was originally coined by Mandelbrot (1983) to describe a family of complex shapes that possess an inherent self-similarity in their geometrical structures. Since then, a wide variety of applications for fractal has been found in many areas of science and engineering. One such area is fractal electrodynamics (Jaggard, 1990, a, b) in which fractal geometry is combined with electromagnetic theory for the purpose of investigating a new class of radiation, propagation, and scattering problems. One of the most promising areas of fractal electrodynamics research is its application to the antenna theory and design.

Another prominent benefit that has been derived from using fractal geometries in antenna has been to design for multiple resonances (Gianvittorio, 2003; Jaggard, 1990b). Fractals are complex geometric shapes that repeat themselves, and are thus self similar. Because of the self-similarity of the geometry due to the iterative generating process, the multiple scales of the recurring geometry resonate at different frequency bands.

Fractals represent a class of geometries with very unique properties that can be attractive for antenna designers. Fractal space filling contours, meaning electrically large features can be efficiently packed into small area. Since the electrical lengths play such an important role in antenna design, this efficient packing can be used as viable miniaturization technique. The space filling properties lead to curves that are electrically very long, but fit into a compact physical space. This property can lead to the miniaturization of antenna elements (Cohen, 2005).

Microstrip antennas offer many advantages such as low profile, the ease of fabrication, and the low cost. These make them very popular and attractive for the designers since the early days they appear. In many cases, where the antenna size is considered an important limitation, their large physical size, make them improper to be used in many applications. Several methods have been considered to reduce the antenna size such as the use of shorting posts (Kumar and Ray, 2003), material loading and geometry optimization (Shrivervik, et al., 2001). Use of slots with different shapes in microstrip patch antennas had proved to be satisfactory in producing miniaturized elements (Kosiavas, et al., 1989; Palaniswamy and Crag, 1985; Chen, 2006). Recently more research works have been devoted to make use of the space-filling property of some fractal objects to produce miniaturized antenna elements (El-Khamy, 2004).

In this paper, a novel pre-fractal microstrip patch antenna design has been presented as a candidate for use in the modern compact and multi-function communication systems. The proposed structure has been generated based on the square patch (the initiator) by applying the Koch fractal curve as the generator. The generator is composed of four segments with equal length, Fig.1a. The proposed antenna is expected to possess a considerable miniaturization owing to its remarkable space filling property. The proposed fractal microstrip antenna structures exhibit a multiband behavior depending on the degree of self-similarity involved in its substructures.

ANTENNA GENERATION PROCESS

The starting pattern for the proposed antenna as a fractal is the square patch, Fig. 1b. From this starting pattern, each of the four sides of the starting pattern is replaced by the generator shown in Fig. 1a. To demonstrate the process the first fourth
iteration steps are shown in Fig.1. The first iteration of replacing a segment with the generator is shown in Fig. 1c. The starting pattern is Euclidean and, therefore, the process of replacing the segment with the generator constitutes the first iteration. The generator is scaled after such that the endpoints of the generator are exactly the same as the starting line segment. In the generation of the true fractal the process of replacing every segment with the generator is carried out an infinite number of times. The resulting pre-fractal structure has the characteristic that the perimeter increases to infinity while maintaining the volume occupied. This increase in length decreases the required volume occupied for the pre-fractal antenna at resonance. It is found that:

\[ P_n = \left(\frac{4}{3}\right) P_{n-1} \]  

where, \( P_n \) is the perimeter of the \( n^{th} \) iteration pre-fractal structure. Theoretically as \( n \) goes to infinity the perimeter goes to infinity. The ability of the resulting structures to increase its perimeters in the successive iterations was found very triggering for examining its size reduction capability as a microstrip antenna. It has been concluded that the number of generating iterations required to reap the benefits of miniaturization is only few before the additional complexities become indistinguishable (Gianvittorio, 2003; Gianvittorio and Rahmat-Samii, 2002).

The presence of the irregular radiating edges in these pre-fractal antenna structures is a way to increase the surface current path length compared with that of the conventional square patch antenna, Fig. 1b; resulting in a reduced resonant frequency or a reduced size antenna if the design frequency is to be maintained.

The length \( L_0 \) of the conventional square patch antenna, Fig.1a, has been determined using the classical design equations reported in the literatures (Bahl and Bhartia, 1980; James and Hall, 1989) for a specified value of the operating frequency and given substrate properties. This length represents approximately half the operating wavelength. As shown in Fig 1, applying geometric transformation of the generating structure (Fig. 1a) on the square patch antenna (Fig. 1b), results in the patch antenna (Fig. 1c). Similarly successive antenna shapes, corresponding to the subsequent iterations can be produced as successive transformations have been applied (Fig.1d-f).

At the \( n \)-th iteration, the corresponding pre-fractal enclosing area, \( A_n \), has been found to be:

\[ A_n = \left(1 - \frac{2^{2n-1}}{3^{2n}}\right) A_{n-1} \]  

The dimension of a fractal provides a description of how much a space it fills (Falconer, 2003). It is a measure of the prominence of the irregularities when viewed at very small scales. A dimension contains much information about the geometrical properties of a fractal. It is possible to define the dimension of a fractal in many ways, some satisfactory and other less so. It is important to realize that different definitions may give different values of dimension for the same fractal shape, and also have very different properties (Falconer, 2003; Peitgen, et al., 2004).

The fractal dimensions of the fractally generated structures up to the 2\(^{nd}\) iteration have been calculated using the box counting method. Box counting is one of the most widely used methods to determine the fractal dimension. Its popularity is largely due to its relative ease of mathematical calculation and empirical estimation [Baumann, 2005]. Fractal dimensions structures with zero, 1\(^{st}\), and 2\(^{nd}\) iterations have been found to be 2, 1.93, and 1.92 respectively. It is worth to note here that the dimension of the zero iteration structure (square) is 2, which is integer number. That is because this
structure is Euclidean and not a fractal, while other non-integer dimensions assure the fractal geometry of their corresponding structures.

**THE PROPOSED ANTENNA DESIGN**

The calculations of the square microstrip patch antenna length are based on the transmission-line model (Ammam, 1997). The length $L_o$ is slightly less than a half wavelength in the dielectric. The calculation of the precise value of the dimension $L_o$ is carried out by an iterative procedure. An initial value of $L_o$ is obtained using:

$$L_o = \frac{c}{2 f_o \sqrt{\varepsilon_r}} \quad (3)$$

where, $f_o$ is the design frequency, $\varepsilon_r$ is the relative dielectric constant of the microstrip substrate, and $c$ is the velocity of light. A value for the effective relative dielectric constant $\varepsilon_{\text{eff}}$ with a patch width, $W_o$ to substrate height ratio $W_o/h \geq 1$, by means of Equ.6 for the square patch antenna (Bahl and Bhartia, 1980; James and Hall, 1989):

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( \frac{1}{\sqrt{1+12h/L_o}} \right) \quad (4)$$

where, $h$ is the substrate height. With the value of $\varepsilon_{\text{eff}}$, calculated by Equ.4, the fringe factor $\Delta L_o$ may now be calculated using:

$$\Delta L_o = 0.412h \left( \frac{\varepsilon_{\text{eff}} + 0.333(W/h + 0.262)}{\varepsilon_{\text{eff}} - 0.258(W/h + 0.813)} \right) \quad (5)$$

Finding the value of $\Delta L_o$, then, $L_o$ can be calculated by:

$$L_o = \frac{c}{2 f_o \sqrt{\varepsilon_{\text{eff}}}} - 2\Delta L \quad (6)$$

The substrate used in the modeling the entire antenna structures presented in this paper, has a relative dielectric constant of 2.2 and substrate height of 1.575 mm. With this substrate, the value of $L_o$, at a design frequency of 2.4 GHz, is found to be of about 41.35 mm.

Equ.1 predicts larger lengths for the 1st and the 2nd iteration antenna structures. This, of course, leads to reduced resonance frequencies. In this paper, the modeling process is planned to maintain the design frequency of 2.4 GHz, which means reduced sizes have to be obtained. Accordingly, the resulting patch lengths are found to be 31.01 mm and 23.25 mm respectively. The corresponding values of patch widths are found to be 31.83 mm and 23.87 mm respectively, taking into account the prescribed range of the orthogonal dimensions ratio. The resulting dimensions indicate that the these patch antennas possess size reductions of about 43.75% and 68.38% respectively compared with the conventional square patch antenna.

As in the case of the conventional rectangular patch antenna, the use a substrate with a higher relative dielectric constant would result in a more size reduction. The length, $L_o$, is inversely proportional to the square root of the relative dielectric constant of the substrate material, $\varepsilon_r$ [Bahl and Bhartia, 1980; Kumar and Ray, 2003].

At the design frequency, the dimensions of five antenna structures, corresponding to the initiator and the first four fractal iterations, have been calculated. These dimensions and the corresponding size reduction percentages are summarized in Table I, using the prescribed substrate parameters. Table I demonstrates how the proposed design technique is powerful in getting interesting size reduction percentages with few iterations.
TABLE I
Summary of the dimensions and the size reduction percentages of the pre-fractal antennas up to 4th iteration

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>( L_n ) (mm)</th>
<th>( W_n ) (mm)</th>
<th>Size Reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square patch</td>
<td>41.35</td>
<td>42.45</td>
<td>-----</td>
</tr>
<tr>
<td>1st iteration</td>
<td>31.0</td>
<td>31.83</td>
<td>43.75</td>
</tr>
<tr>
<td>2nd iteration</td>
<td>23.25</td>
<td>23.87</td>
<td>68.38</td>
</tr>
<tr>
<td>3rd iteration</td>
<td>17.44</td>
<td>17.90</td>
<td>82.21</td>
</tr>
<tr>
<td>4th iteration</td>
<td>13.08</td>
<td>13.43</td>
<td>89.98</td>
</tr>
</tbody>
</table>

PERFORMANCE EVALUATION
For comparison purposes, the conventional square microstrip patch antenna has been analyzed (considered to constitute the zero iteration structure), together with the resulting pre-fractal antenna structures resulting from the 1st and 2nd iterations using the commercially available software IE3D, from Zeland Software Inc. This EM simulator carries out the performance evaluation of 3D electromagnetic structures using the method of moments (MoM).

Microstrip patch antennas are characterized by its moderate gain. The gain depends amongst many other parameters, on the physical aperture of the antenna. Since this work aims to present compact size antennas, the use of the conventional coaxial probe feed will result in poor radiation performance. To enhance the proposed antenna performance, a special feeding technique has been used. This technique is called the L-probe feed [Hazdra and Mazanek, 2006; Mak, et al., 2002]. In this technique, an air-gap is inserted between the lower side of antenna substrate and its ground plane. The probe is placed in the air-gap and it is composed of two parts; vertical and horizontal. The horizontal part is beneath and parallel to the substrate, while the vertical one is attached to the ground plane from one side and to the horizontal part from the other side forming an L-shaped feeding structure. Tuning of both the vertical and the horizontal lengths of the probe leads to the best matching condition, and hence the optimal antenna radiation performance can be obtained.

Each of the modeled antennas is located at the point (0,0,0) with respect of the coordinate system and fed with an L-probe feed as depicted in Fig.2, where the 2nd iteration fractal microstrip patch antenna is shown. Fig.3 shows the return loss response of the conventional square (zero iteration) patch antenna fed with an L-probe having a vertical length of 8.0 mm and a horizontal length of 21.5 mm. Fig.3 indicates that this antenna produces a single resonance at the 2.4 GHz design frequency with a bandwidth of about 0.7 GHz, which is considerably greater than that of the same antenna when fed by the conventional coaxial probe. Figs.4 and 5 show the \( E_0 \) and \( E_\phi \) and the total \( E \)-field radiation patterns respectively, while Fig.6 show the 3-D radiation pattern at the design frequency. It is obvious that the square patch antenna exhibits satisfactory radiation characteristics as compared with the conventional probe feed.

Similarly, the performance curves of the 1st and 2nd iteration fractal microstrip patch antenna are depicted in Figs.7-13 and Figs.14-20 respectively. Return loss responses for these antennas are shown in Fig.7 and Fig.14 respectively. The corresponding responses clearly demonstrate the multi-frequency behavior of these two antennas. This doesn’t prevent the possibility of existence other resonances beyond the modeling frequency range. The resonances are expected to increase with further iterations. Figs.10, 13, 17, and 20 points out to the radiating parts responsible to the corresponding resonance.

CONCLUSION
A novel fractal patch antenna design based on Koch fractal curve has been presented in this paper, for use in the modern multiband compact wireless
applications. The proposed antenna structure showed high degree of self-similarity and space-filling properties.

The resulting antenna structures had shown to possess size reductions of about 43.75% and 68.38%, for the first and second iterations respectively. These size reductions are expected to be developed further to 82.21% and 89.98% for antenna structures corresponding to the 3rd and 4th iterations. It is expected that the antenna presented in this paper will have a variety of applications in wireless applications.

It has been found that the modeled fractal antennas have a multi-resonance behavior with more than sufficient fractional bandwidths for most of the wireless applications as a result of employing an L-probe feed. Careful tuning of the feed vertical and horizontal parts has been found helpful in getting best matching conditions in a considerably reliable manner.

Additional work could be carried out to explore its performance in many wireless mobile applications, where the production of circular polarization with acceptable axial ratios through the specified bandwidths represents a serious requirement, besides the miniaturization and the multi-frequency performance.

REFERENCES


Fig. 1 The generation process of the proposed fractal microstrip patch antenna structures based on fractal Koch curve. (a) the generator, (b) the initiator (square patch antenna), (c) the 1st iteration, (d) the 2nd iteration, (e) the 3rd iteration, and (f) the 4th iteration pre-fractal structures.

Fig. 2 The antenna layout with respect to the coordinate system.

Fig. 3 The return loss response for the zero iteration pre-fractal microstrip patch antenna.
Fig. 4 $E_\theta$ and $E_\phi$ radiation patterns of the square microstrip patch antenna at 2.4 GHz.

Fig. 5 The total E field radiation pattern of the square in elevation at 2.4 GHz.

Fig. 6 The 3-D radiation pattern of the square microstrip patch antenna at 2.4 GHz.

Fig. 7 The return loss response for the 1st iteration pre-fractal microstrip patch antenna.
Fig. 8 $E_\theta$ and $E_\phi$ radiation patterns of the 1st iteration fractal microstrip patch antenna at 2.4 GHz.

Fig. 9 The total E field radiation pattern of the 1st iteration fractal microstrip at 2.4 GHz.

Fig. 10 The current density at the surface of the 1st iteration fractal microstrip at 2.4 GHz.

Fig. 11 $E_\theta$ and $E_\phi$ radiation patterns of the 1st iteration fractal microstrip patch antenna at 7.6 GHz.
Fig. 12 The total E field radiation pattern of the 1st iteration fractal microstrip at 7.6 GHz.

Fig. 13 The current density at the surface of the 1st iteration fractal microstrip at 7.6 GHz.

Fig. 14 The return loss response for the 2nd iteration pre-fractal microstrip patch antenna.

Fig. 15 $E_\theta$ and $E_\phi$ radiation patterns of the 2nd iteration fractal microstrip patch antenna at 2.4 GHz.
Fig. 16  The total E field radiation pattern of the 2\textsuperscript{nd} iteration fractal microstrip at 2.4 GHz.

Fig. 17  The current density at the surface of the 2\textsuperscript{nd} iteration fractal microstrip at 2.4 GHz.

Fig. 18  $E_\theta$ and $E_\phi$ radiation patterns of the 2\textsuperscript{nd} iteration fractal microstrip patch antenna at 7.1 GHz.

Fig. 19  The total E field radiation pattern of the 2\textsuperscript{nd} iteration fractal microstrip at 7.1 GHz.
Fig. 20 The current density at the surface of the 2nd iteration fractal microstrip at 7.1 GHz.