A printed fractal based slot antenna for multi-band wireless communication applications

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A Printed Fractal Based Slot Antenna for Multi-band Wireless Communication Applications

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Abstract— Different slot structures have been widely used in numerous designs to produce antennas with enhanced bandwidths. In this paper, a printed slot antenna has been introduced as a candidate for use in the multi-band wireless communication applications. The antenna slot structure has a rectangular shape with its width, from the side of feed, has been modified in the form of Koch fractal curve of the second iteration. The antenna has been fed with 50 Ohm microstrip transmission line etched on the reverse side of the substrate. Modeling and performance evaluation of the proposed antenna design have been carried out using a method of moments based EM simulator, IE3D. Simulation results show that the resulting antenna exhibits a multi-resonant behavior making it suitable for a wide variety of multi-band wireless communication applications. The first resonant band, centered at 2.58 GHz, extends from 2.40 to 2.89 GHz. This band covers the 2.4 GHz WLAN band (frequency range 2.4–2.483 GHz) and the 2.5 GHz mobile WiMAX operating band (frequency range 2.5–2.7 GHz). The second resonant band, centered at 4.03 GHz, extends from 3.40 to 4.50 GHz. This band covers the 3.5 GHz mobile WiMAX operating band (frequency range 3.4–3.6 GHz). While the third resonant band centered at 5.74 GHz, extends from 5.42 to 6.18 GHz. This band covers the U-NII mid-band (frequency range 5.47–5.725 GHz) and U-NII high-band (frequency range 5.725–5.875 GHz). Parametric study has been carried out to explore the effect of varying the antenna feed line length on its performance.

1. INTRODUCTION

The term fractal, which means broken or irregular fragments, was originally coined by Mandelbrot [1] to describe a family of complex shapes that possess an inherent self-similarity in their geometrical structures. A wide variety of applications for fractal has been found in many areas of science and engineering. One such area is the fractal electrodynamics [2, 3] 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 has been to design antenna with multiple resonances [3, 4]. 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.

Hilbert, Peano, and Gosper space-filling curves have attracted the researchers to achieve antenna miniaturization with multiple resonances [5–14]. Many Hilbert fractal-based structures have been proposed to produce printed and microstrip dipole and monopole antennas with compact size and multiband performance for different applications [5–11]. Peano space-filling curves have also drawn the interest of many research groups, where different aspects of many Peano fractal antennas have been reported [11–14]. Gosper space-filling curve has been used to model reduced size multiband antenna [15]. Moreover, structures based on these space-filling geometries have been successfully used in different ways to form parts (or the whole) of the ground plane of miniature and multiband antennas [16]. It is worth to note that, in the majority of the published works, the different types of space-filling curves have been used to model dipole and monopole antennas. Slot antennas based on space-filling curves have drawn less attention from antenna designers; to name a few [10, 17–20].

In this paper, a printed slot antenna structure has been introduced as a candidate for use in the modern compact and multi-function communication systems. The proposed structure has a rectangular slot shape with one of its sides has been modified to be in the form of the second iteration Koch fractal curve. The proposed antenna is expected to possess a considerable compact size owing to the space filling property of the Koch fractal curve.

2. THE PROPOSED ANTENNA STRUCTURE

The starting pattern for the proposed antenna as a fractal is the straight line segment, Figure 1(a). From this starting pattern, this straight line segment is replaced by the generator shown in Figure 1(b). To demonstrate the process, the first three iteration steps are shown in Figure 1.
The resulting pre-fractal structure has the characteristic that the length increases to infinity while maintaining the space occupied [21]. This increase in length decreases the required space occupied for the pre-fractal antenna at resonance. It is found that:

\[ L_n = \left( \frac{4}{3} \right)^n L_0 \]  

where, \( L_n \) is the length of the \( n \)th iteration pre-fractal structure. The ability of the resulting structures to increase its length 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 [4].

The presence of the irregular radiating edges in the pre-fractal based slot antenna structures is a way to increase the surface current path length compared with that of the conventional rectangular slot antenna, Figure 2; resulting in a reduced resonant frequency or a reduced size antenna if the design frequency is to be maintained. The geometry of the proposed fractal shaped slot antenna is shown in Figure 2. The rectangular slot has been constructed with one its sides takes the form of the 2nd iteration Koch curve, on the ground plane side of a dielectric substrate. The dielectric substrate is supposed to be the FR4 with a relative dielectric constant of 4.4 and thickness of 1.6 mm. The slot antenna is fed by a 50 Ω microstrip line printed on the reverse side of the substrate. The microstrip line, with a width of 3.0 mm, is placed on the centreline of the slot structure (\( x \)-axis).

### 3. THE ANTENNA DESIGN

A rectangular slot antenna, with one of its side lengths based on the 2nd iteration Koch pre-fractal curve, has been designed for the ISM band applications at 2.4 GHz. Observing the influence of the various parameters on the antenna performance, it has been found that the dominant factor in the proposed antenna is the slot external perimeter, \( L_{\text{ext}} \). At first, the external perimeter of the slot structure, that matches the resonant frequency, has to be calculated in terms of the guided
wavelength $\lambda_g$ which is given by:

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}}}} \quad (2)$$

where $\varepsilon_{\text{eff}}$ is the effective dielectric constant.

For $n$th iteration Koch fractal curve, the external perimeter $L_{\text{ext}}$ of the antenna slot structure, shown in Figure 2, can be formulated as:

$$L_{\text{ext}} = 2W + L \left( 1 + \left( \frac{4}{3} \right)^n \right) \quad (3)$$

Then the lowest resonant frequency, $f_{01}$, relative to twice the slot external side length is formulated by:

$$f_{01} = \frac{C_0}{2L_{\text{ext}}\sqrt{\varepsilon_{\text{eff}}}} \quad (4)$$

where $C_0$ is the speed of light in free space. Higher order resonances are attributed to the smaller self-similar structures constituting the slot.

4. ANTENNA PERFORMANCE EVALUATION

The fractal based slot antenna with the layout, depicted in Figure 2, has been modeled and analyzed using a method of moments based EM simulator IE3D, from Zeland Software Inc. [24].

Simulation results show that the slot dimensions matching the specified first resonant frequency, $f_{01}$, are: $L = 23.4$ mm, and $W = 32.78$ mm. According to (3), the slot external length has been found to be of about 137.85 mm. This is in good agreement with the resulting resonant frequency as calculated using (4). The microstrip line feed length has an affective role in different degrees to establish the matching levels at the rest resonances. However, the variation of the feed line length, measured away from the slot center, has been demonstrated in Figure 3, for feed line length varies in steps of 2 mm with respect to the antenna slot center. Different values of the feed line length result in different responses as a result of coupling satisfied at each length. This makes the antenna suitable for single or multi-band applications.

Figure 4 shows the resulting antenna return loss response for a feed line length of 3 mm away from antenna center. The antenna exhibits an impedance bandwidth, for $S_{11} \leq -10$ dB, which constitutes three resonances in the swept frequency range 0–7 GHz. The first resonant band, centered at 2.58 GHz, extends from 2.40 to 2.89 GHz. This band covers the 2.4 GHz WLAN band (frequency range 2.4–2.483 GHz) and the 2.5 GHz mobile WiMAX operating band (frequency range 2.5–2.7 GHz). The second resonant band, centered at 4.03 GHz, extends from about 3.40 to 4.50 GHz. This band covers the 3.5 GHz mobile WiMAX operating band (frequency range 3.4–3.6 GHz). While the third resonant, band centered at 5.74 GHz, extends from 5.42 to 6.18 GHz. This band covers the U-NII mid-band (frequency range 5.47–5.725 GHz) and U-NII high-band (frequency range 5.725–5.875 GHz).

Figure 3: Return loss responses of the modeled antenna with the feed line length as the parameter.

Figure 4: Return loss response of the modeled antenna with a feed line length of 3 mm away from the center.
Figure 5: The 2D E-field radiation patterns of the modeled fractal slot antenna with a feed line length equals to 3 mm away from the center, at 2.5, 3.5, and 5.5 GHz.

Figure 6: The surface current distributions on the slot structure of the modeled antenna with a feed line length equals to 3 mm away from the center, at 2.5, 3.5, and 5.5 GHz.

The 2D radiation patterns at specified frequencies through the three bands have been shown in Figure 5, where an average gain of about 2.5 dB has been satisfied. The antenna almost offers omnidirectional radiation patterns. The surface current distribution on the slot structure at 2.5, 3.5, and 5.5 GHz are shown in Figure 6, where it has been clearly depicted the parts of the slot structure that contribute in the radiation at each assigned frequency. Additional work has to be carried out to explore the effects of Koch fractal curve indentation angle on the antenna performance. It is expected to gain interesting features with antenna performance that supports the operating band of many other communication services.

5. CONCLUSIONS

A fractal shaped slot antenna design based on the second iteration Koch fractal curve has been presented in this paper, for use in the modern multiband compact wireless applications. It is expected that the antenna presented in this paper will have a variety of applications in wireless applications. Simulation results show that the modeled fractal antennas have a multi-resonance behavior with fractional bandwidths sufficient for most of the wireless applications. Careful tuning of the feed has been found helpful in getting best matching conditions in a considerably reliable manner. Additional work has to be carried out to explore the performance of the proposed antenna when varying the indentation angle of the Koch fractal curve. This will, absolutely, result in different multi-resonant frequency allocations which might be suitable for many wireless communication applications.

REFERENCES