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A New Reduced Size Multiband Patch Antenna Structure Based on Minkowski Pre-Fractal Geometry

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Abstract: A novel compact Minkowski Pre-fractal antenna is investigated to be an efficient scheme of miniaturization. Based on the simulation results, the proposed antenna has shown to posses an excellent size reduction possibility with good radiation performance for wireless applications. Compared with the conventional square patch microstrip antenna and the square microstrip antenna with two pairs of slits at edges, the presented antenna exhibits high size reduction, wider impedance-bandwidth performance and multi-frequency operation with acceptable radiation characteristics. Moreover, with the novel geometry, the designer will have a high degree of freedom that can be used to reduce further the antenna size.

Key words: Minkowski-Like pre-fractal, microstrip antenna, multiband antenna, antenna miniaturization

INTRODUCTION

A fractal is recursively generated object having a fractional dimension. The term fractal, which means broken or irregular fragments, was originally coined by Mandelbort (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 (Jaggard, 1990b; Gianvittorio, 2003). 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 geometry 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.

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, 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 study, a novel pre-fractal structure has been analyzed to be used as a patch antenna candidate. The proposed structure has been generated fractally in a manner like that adopted in the generation of Minkowski pre-fractal based on square patch (the initiator).The only difference is that, the generator in the later case is composed of 3 segments with equal length, while in the present case, it is composed of three segments with the middle segment length being much less than the other two segments. Because of this, the proposed antenna is referred to as Minkowski-Like Pre-Fractal (MLPF). Based on simulation results, the MLPF exhibited good miniaturization ability owing to the space filling properties. As in the case of all antennas having fractal geometries, the MLPF patch antenna shows a multiband operation depending on the degree of self similarity it possesses (Cohen, 2005).

Antenna generation process: The starting pattern for the proposed antenna as a fractal is a square 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 two iterations are shown. 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 replaced an infinite number of times. The generator is composed of three segments. The middle, W_1, segment is chosen such that it is much less than the other two end segments. The other two segments are tuned to adjust the overall perimeter of the fractal length. This tuning length is called the indentation width, W_2 (Gianuittorio, 2003). 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:

$$P_n = (1 + 2a_2)P_{n-1} \tag{1}$$

Where P_n is the perimeter of the nth iteration pre-fractal and a_2 is the ratio W_2/L_0.

Theoretically as n goes to infinity the perimeter goes to infinity. The ability of the resulting structure to increase its perimeter at every iteration 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 Yahya, 2002).

The basic idea of the proposed antenna structure has been extracted from a comparative study of both the conventional square patch antenna, Fig. 1b and the square microstrip antenna with two pairs of orthogonal slits at the edges, Fig. 1c. The presence of slits in this antenna 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 maintained. The space filling geometry and the self similarity that MLPF1 antenna in Fig. 1c possesses make it analogous to the modified square microstrip antenna reported in the literature (Kumar, 2003; Huang *et al.*, 1998). It is expected then, that the second iteration MLPF2, shown in Fig, 1d will exhibit further miniaturization ability owing to its extra space filling property. Theoretically the size reduction process goes on further as the iteration steps increase.

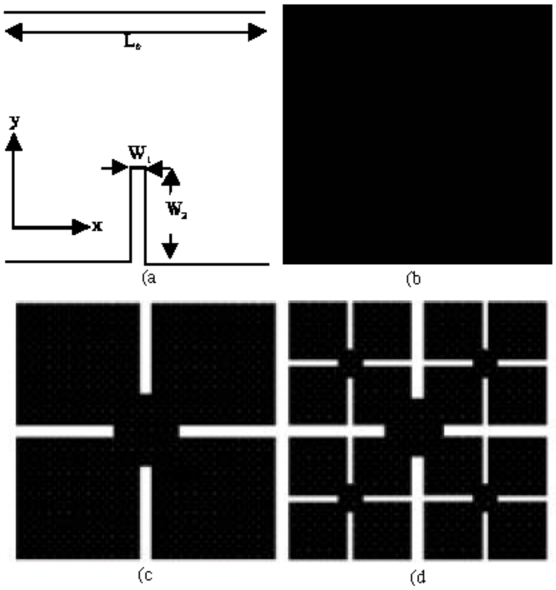

Fig. 1: Construction of the Minkowski-Like Pre-Fractal (MLPF) structure. (a). The generator, (b). Square patch microstrip antenna, MLPF0 (the initiator), (c). MLPF1 (first iteration) and (d). MLPF2 (second iteration)

The length L_o of the conventional square patch, MLPF0, antenna has been determined using the classical design equations reported in the literature (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.

The MLPF1 antenna has been designed with equal slot lengths. The indentation length, W_2 is adjusted to the resonance frequency. As a rough estimate of this length, it has been found that W_2 plus L_1 is approximately equal to L_o. The middle segment width W_1 is chosen such that it is much less than the indentation length (Huang *et al.*, 1998). As shown in Fig 1, applying geometric transformation of the generating structure (Fig. 1a) on the square patch antenna (Fig. 1b), results in the square patch antenna with 2 pairs of orthogonal slits at the edges

(Fig. 1c). Similarly successive antenna shapes, corresponding to the following iterations can be produced as successive transformations have been applied.

At the n-th iteration, the corresponding MLPF antenna length has been found to be:

$$L_n = (0.6)^{n/2} L_0 \tag{2}$$

While the enclosing area, A_n, has been found to be:

$$A_n = (0.6)^n A_0 \tag{3}$$

Where A_0 is the enclosing area of the conventional MLPF0 square patch antenna.

The dimension of a fractal provides a description of how much a space it fills. 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.

According to Falconer (2003) since the generator used to develop the proposed MLPF structure involves similarity transformations of more than one ratio; a_1 and a_2, its dimension can be obtained from the solution of the following equation:

$$2(\frac{1}{2}(1-a_1))^s + 2a_2^{\,s} + a_1^{\,s} = 1 \tag{4}$$

Where s, represents the dimension, a_1 is the ratio W_1/L_0 and a_2 is as defined earlier. Then the dimension of the proposed structure, according to Eq. 4 is equal to 1.586. This value of dimension has been obtained for values of a_1 = 0.05 and a_2 = 0.35.

THE PROPOSED ANTENNA DESIGN

The calculations of the square microstrip antenna length are based on the transmission-line model (Derneryd, 1766; Ammam, 1997). The width W of the radiating edge, which is not critical, is chosen first. The length L_0 is slightly less than a half wavelength in the dielectric. The calculation of the precise value of the dimension L_0 of the square patch is carried out by an iteration procedure. An initial value of L_0 is obtained using:

$$L_0 = \frac{c}{2f_0\sqrt{\varepsilon_r}} \tag{5}$$

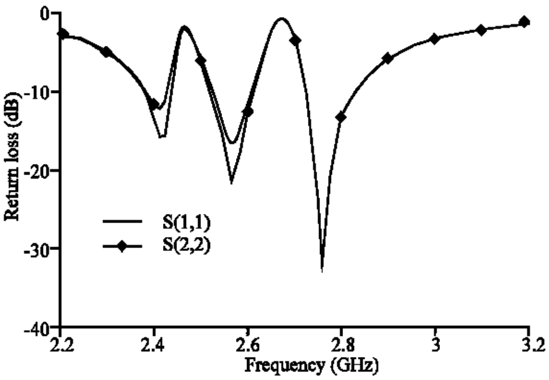

Fig. 2: Simulated return loss of the MLPF2 antenna

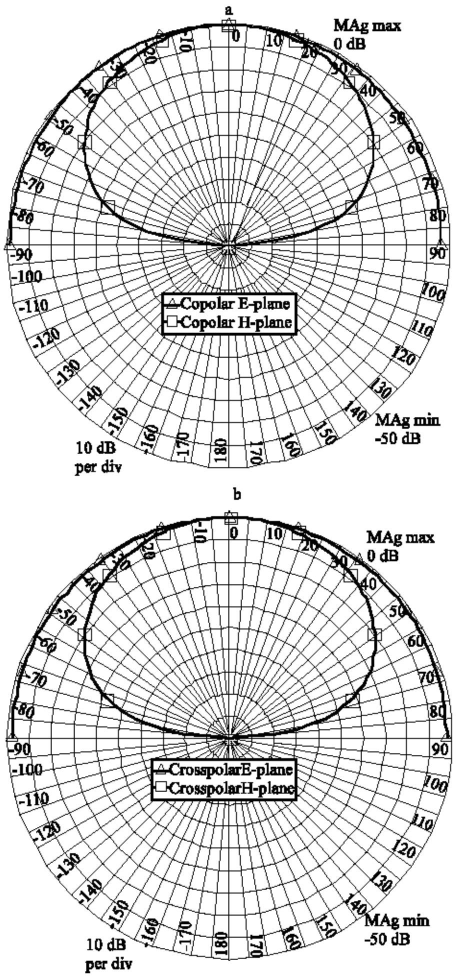

Fig. 3: MLPF2 antenna radiation patterns at 2.43 GHz, (a). E and H planes copolar and (b). E and H planes cross-polar

For a frequency of 2.45 GHz and using FR4 substrate with a relative dielectric constant of 4.4 and a substrate height of 1.6 mm, this yields the value L_0 = 29.20 mm. A value for the effective relative dielectric constant ε_{eff}, with

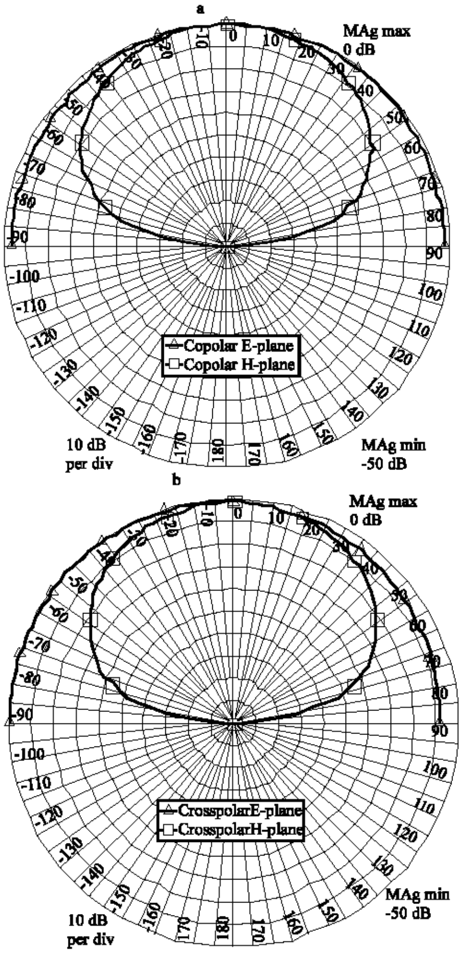

Fig. 4 : MLPF2 antenna radiation patterns at 2.57 GHz, (a). E and H planes copolar and (b). E and H planes cross-polar

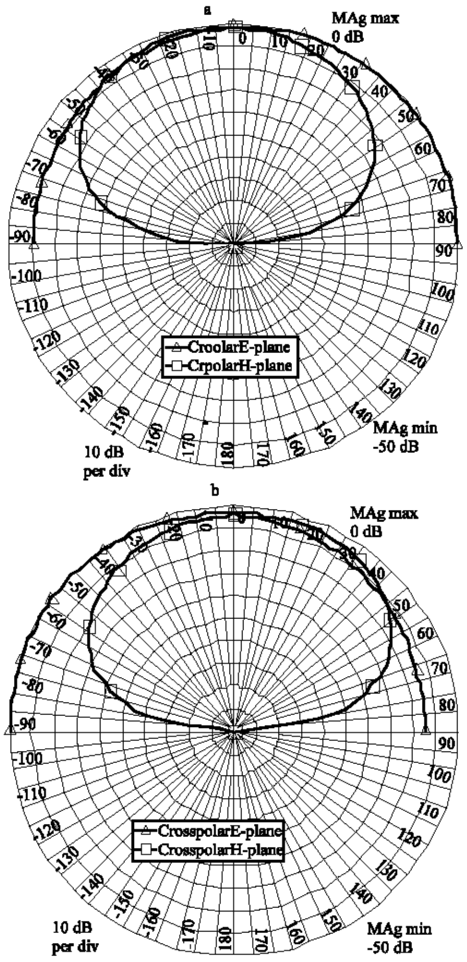

Fig. 5: MLPF2 antenna radiation patterns at 2.76 GHz, (a). E and H planes copolar and (b). E and H planes cross-polar

$W/h \geq 1$ by means of Eq.6 for the square patch antenna (James and Hall, 1989; Bahl and Bhartia, 1980; Ammam, 1997):

$$\varepsilon_{eff}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon-1}{2}\left(\frac{1}{\sqrt{1+12h/L_0}}\right) \qquad (6)$$

It is found that $\varepsilon_{eff} = 4.02$. With this value of ε_{eff}, the fringe factor ΔL_o, may now be calculated using:

$$\Delta L_0 = 0.412h\frac{(\varepsilon_{eff}+0.333)(W/h+0.262)}{(\varepsilon_{eff}-0.258)(W/h+0.813)} \qquad (7)$$

The value of ΔL turns out to be 0.735 mm and by means of Eq. 8:

$$L_0 = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 2\Delta L \qquad (8)$$

The MLPF1 patch antenna length can be calculated using Eq.1and found to be L_1=21.47 mm. The slit lengths in the x and y-directions are tuned to the resonance (design) frequency and are set to result in a value of about 7.5 mm, with a slit width a of 1mm.

Based on these numerical calculations, the resulting length of the MLPF2 patch antenna has been found to be L_2=16 mm. The resulting dimensions indicate that the MLPF1 and MLPF2 patch antennas possess size reductions of about 40 and 64%, respectively compared with the conventional square patch antenna.

MLPF2 antenna has been analyzed using the commercially available software Microwave Office MWO 2000 v.3.22 (Fig. 2). Performance curves of the MLPF2 patch antenna show interesting features making it as a promising candidate for the use in many wireless applications. The multi-frequency behavior of this antenna, where resonances appear to take place at frequencies of 2.43, 2.57 and 2.76 GHz, with impedance-bandwidths of about 60, 80 and 100 MHz respectively for VSWR = 2. Radiation patterns for the copolar and cross-polar components in the E and H-planes at these frequencies are shown in Fig. 3-5 respectively, where good radiation characteristics are observed.

CONCLUSION

A novel Minkowski-like pre-fractal patch antenna has been presented to be a candidate for use in multiband wireless applications. The proposed antenna structure showed high degree of self-similarity and space-filling properties. The antenna structures had shown to possess size reductions of about 40 and 64%, for the first and second iterations respectively, with good radiation characteristics. This size reduction can be developed further to 78% if an additional iteration is adopted. It is expected that the antenna presented in this study will have a variety of applications in wireless applications.

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