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Published in IET Microwaves, Antennas & Propagation
Received on 14th June 2008
Revised on 19th March 2009
doi: 10.1049/iet-map.2008.0202

ISSN 1751-8725

Dual-frequency characteristics of Minkowski-square ring antennas

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Abstract: Fractal Minkowski curves to design a compact dual-frequency microstrip ring antenna are proposed. Sides of a square ring have been selectively replaced with first and second iterations of the generalised fractal geometry to design a smaller antenna with dual-frequency operation. This behaviour has been explained based on current distributions on the antenna structure. Measured results compare well with electromagnetic simulations.

1 Introduction

Many fractal geometries have been suggested for antenna applications in the recent years [1–3]. In many instances the performance improvements have been generally attributed to the self-similarity of fractals. Theoretical investigations on the relationship between quantifiable fractal characteristics and multi-frequency nature of antennas have been limited to linear antennas such as dipoles [4–6] that are not conformal. Fractal properties that may guarantee multi-frequency and/or wideband antenna characteristics have not been investigated systematically. On the contrary, there have been detailed studies on non-fractal geometries that may out-perform fractals in certain respects [7, 8]. In this context we present a detailed parametric study and analysis of the resonance characteristics of square ring antennas whose sides have been replaced with fractal Minkowski curves.

Indeed, resonance behaviour and size reduction of ring-like geometries have been studied in various contexts in electromagnetics. For example, Hilbert curve fractal geometry variants have been proposed for reducing the area of such geometries in frequency selective surfaces [9, 10]. In the context of planar filters, stub loading of such geometries resulted in significant size reduction [11].

The basic antenna chosen for this study consists of an electromagnetically coupled square ring antenna. The antenna structure (Fig. 1) has three layers: two dielectric layers and an air gap between them [12]. The grounded dielectric layer at the bottom has a transmission line patterned on its top side. The top dielectric layer only has radiating ring on the outer side. The dimensions of the strip on the transmission line does not generally affect the resonant frequency of the radiating ring, but its length and width may have to be tuned to achieve good impedance matching at the resonant frequency. The input impedance is also affected by the height of the air gap between the dielectric slabs. The resonances of such ring antennas correspond to the frequencies at which its electrical length equals a multiple of the wavelength. The width of the ring, the presence of corner discontinuities and the length of the feed strip play a marginal role in the resonant frequency of this antenna. These may however be optimised easily using electromagnetic simulations. Detailed parametric studies and a multi-frequency antenna with multiple square rings based on this configuration are presented in [12].

This antenna with one such ring is essentially a single-frequency antenna. For example, on dielectric stack consisting of two layers of Rogers substrate (RO-3003 with $\varepsilon_r = 3$, $\tan\delta = 0.0013$, thickness = 1.52 mm) separated with an air gap of 0.5 mm, a square ring of mean perimeter of 100 mm and width of 0.5 mm has its first two resonances occurring at 2.19 and 4.42 GHz. However, the second resonant mode of this antenna is not useful as the radiation pattern in this case is not similar to that at the first mode. Hence a square ring antenna cannot be used for

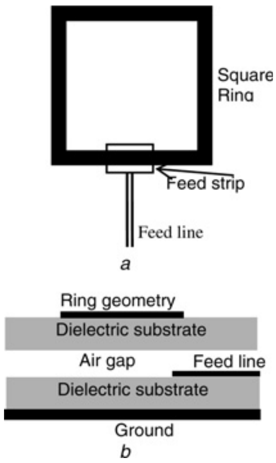

Figure 1 *Schematic of the square ring antenna configuration*

a Top view
b Cross section

dual-frequency applications even though the geometry has multiple resonances. In the following sections we present modifications to this antenna that result in considerable size reduction as well as dual-frequency characteristics. Parametric variations have been studied using numerical simulations. Selected cases have been fabricated and tested for experimentally validating the conclusions from this study.

2 Generalisation of Minkowski curves for dual-frequency antenna

In this study we propose to replace the sides of the square ring by Minkowski curves. For the geometric construction of a fractal Minkowski curve, one starts with the straight line of length l, called the initiator. This is divided into three equal parts of length $(l/3)$ and middle segment is replaced by two vertical and a horizontal segment of equal length (Fig. 2). This procedure may be iterated to result in a self-similar fractal geometry.

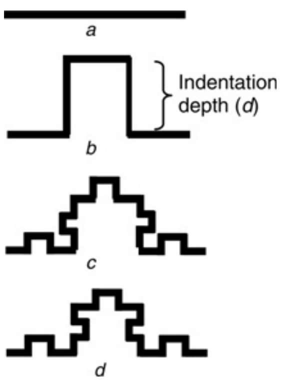

Figure 2 *Generation of Minkowski curves used in this study*

a Initiator
b Generator
c Second iteration (standard)
d Second iteration (modified)

In the present study, an antenna design flexibility is introduced by making the length of this vertical segment in Fig. 2*b* vary relative to that of the horizontal segments. Based on this modification, the aspect ratio for the generator is

$$\text{aspect ratio} = \frac{\text{indentation depth}(d)}{\text{length of horizontal segment}(l/3)}$$

This aspect ratio is maintained at higher iterations during the generation of the geometry. Similar variation is typically exploited in the context of fractal geometries, the resulting configurations are considered fractals and approaches are available for calculating their fractal properties such as Hausdorff dimension [13]. Although d may take any value,

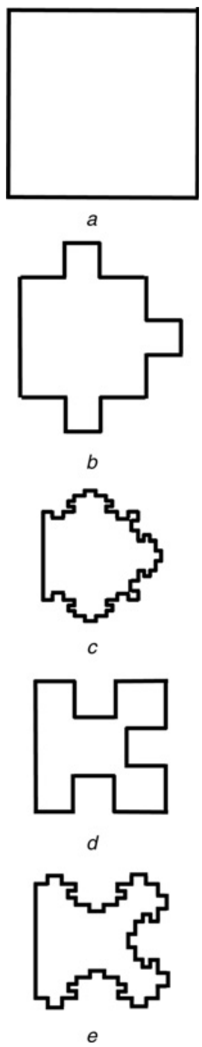

Figure 3 *Mikowski-square ring with sides replaced by fractal geometry on one, two and three sides at first and second iteration*

The feed transmission line (c.f. Fig. 1) is placed symmetrically below the left edge of all these geometries
a Square ring
b Minkowski ring (first iteration, outside)
c Minkowski ring (second iteration, outside)
d Minkowski ring (first iteration, inside)
e Minkowski ring (second iteration, outside)

doi: 10.1049/iet-map.2008.0202

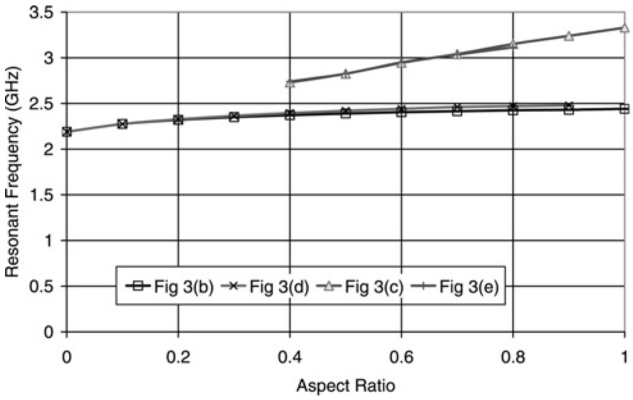

Figure 4 *Primary resonant frequency of various antenna geometries in Fig. 3 as the aspect ratio of the fractal geometry is varied*

segments of the geometry may collide for $d > 1$, and hence such geometries may not be useful in the present antenna design. Furthermore, although the above theoretical analyses consider the geometry as line segments having zero width, for the sake of realising antennas, we used geometries with a width of 0.5 mm. This has effectively limited the maximum order of fractal iterations to two. As indicated by comparing Figs. 2*c* and *d* a minor modification in the generation algorithm ensures that the segments of the geometry do not intersect at the second iteration.

3 Simulation studies

The Minkowski-square antenna studied has the same configuration as in Fig. 1, with the sides of the square replaced with generalised Minkowski curves. Some of the resulting geometries have been compared in Fig. 3. The antenna is designed on a two-layer dielectric consisting of a pair of microwave substrate (RO-3003 with $\varepsilon_r = 3$, $\tan\delta = 0.0013$, thickness = 1.52 mm) separated by an air gap of 0.5 mm. The overall mean perimeter (obtained after unfolding fractals) is kept constant at 100 mm as a reference. Numerical simulations were performed using IE3D for geometries with different aspect ratios and iterations.

We first investigated the possibility of Minkowski-square ring (MSR) antennas by bending the line segments outwards and inwards, as indicated in Fig. 3. It has been found that the resulting resonant frequencies were almost identical. This

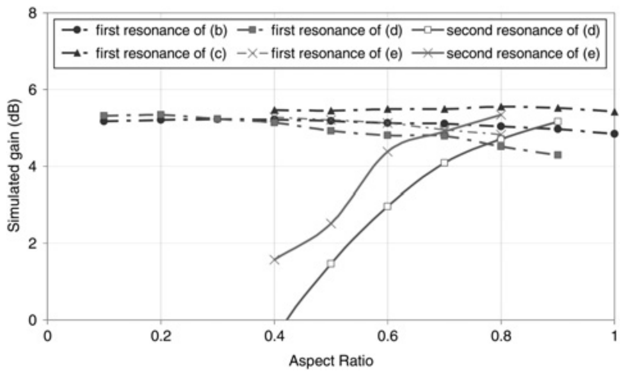

Figure 5 *Variation in the boresight gain of MSR geometries of Fig. 3*

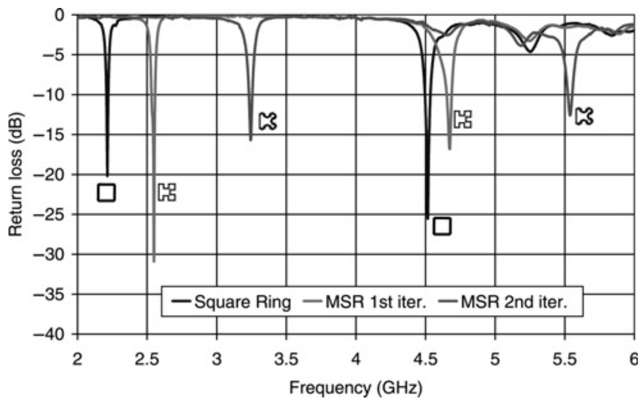

Figure 7 *Measured return loss of the square ring and MSR geometries with aspect ratio of 0.8*

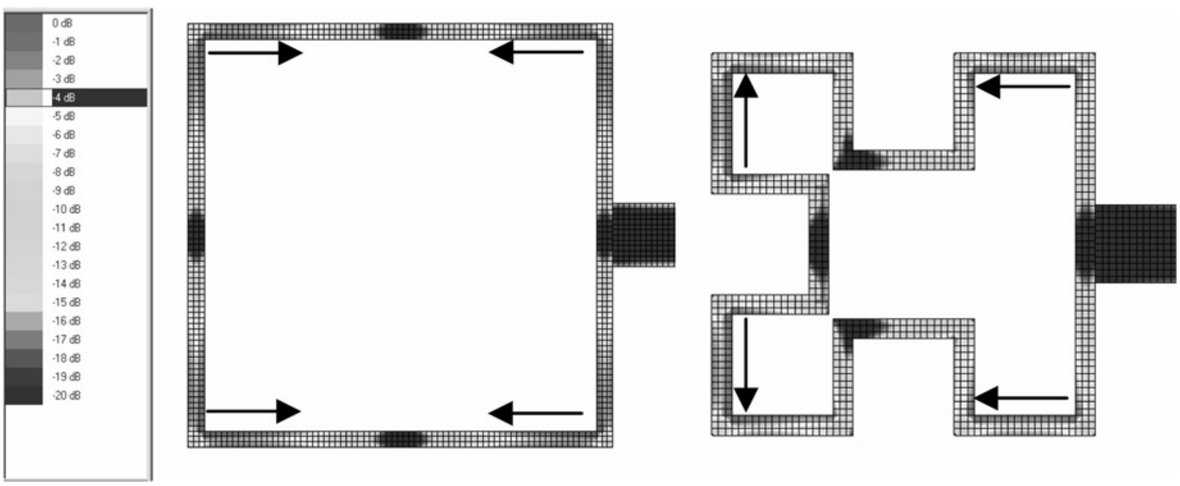

Figure 6 *Average current distribution of antenna geometries by simulations*

Arrows marked close to current maximas

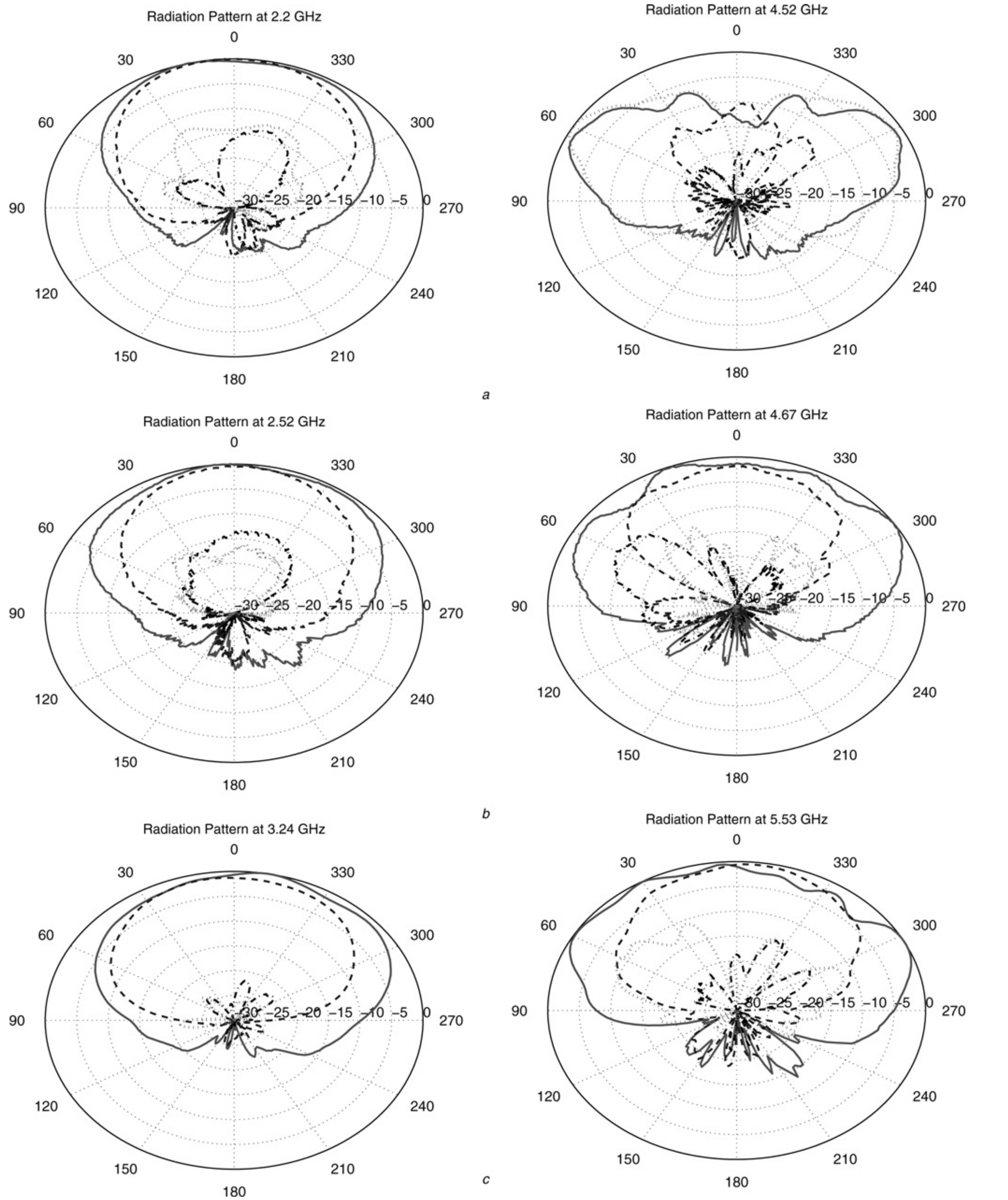

Figure 8 *Measured radiation patterns in E (co: solid, cross: dash-dot) and H (co: dashed, cross: dot-dot) planes at the first and second resonant frequencies of fabricated antennas*

a Square ring antenna
b Minkowski-square antenna (first iteration) Fig. 3*d*
c Minkowski-square antenna (second iteration) Fig. 3*e*

IET Microw. Antennas Propag., 2010, Vol. 4, Iss. 2, pp. 219–224

doi: 10.1049/iet-map.2008.0202

trend was also consistent with the design of ring-type antennas, as the resonant frequency of these antennas depends on the perimeter of the ring geometry. However, geometries with outward projections require relatively larger area than the others. Hence in the case of geometries *d* and *e* in Fig. 3, as the indentation depth is increased, the area occupied by the geometry reduces. This size reduction aspect is consistent with the widely acknowledged advantage of using fractal geometries of topological dimension of one in antennas where the linear dimension plays a major role in deciding the radiation characteristics. For the set of antennas studied, this approach resulted in a reduction of 42% in area, compared to an equivalent square antenna with the same resonant frequency [14].

However, as indicated in Fig. 4, as the aspect ratio is varied, the resonant frequency changes even though the mean perimeter is kept the same. This variation may be attributed to the apparent loss or gain in the electrical length by the introduction of bends for accommodating fractals. Discontinuities at corners and mutual reactances between adjacent line segments may contribute to this. These indicate that the effect of introducing this fractal geometry and varying its aspect ratio is in the effective electrical perimeter of the geometry. It may also be of interest to note that both types of geometries in Fig. 3 behave similarly as the indentation depth is varied.

As shown in Fig. 5, the boresight (axial) gain of this type of antennas also depends on the aspect ratio. The gain at the primary resonance marginally drops as the aspect ratio is increased. Significant differences are observed at the second resonant frequency. The antennas with fractal geometries projected inwards to the square Figs. 3*d* and *e* resulted in a dramatic increase in the boresight gain at the second resonant frequency as the aspect ratio is increased. The boresight gain characteristics of these antennas at their second resonance become comparable to those at the first resonance for geometries with aspect ratio above 0.7 for both the first- and second-iteration geometries. It may be recalled that the square ring antenna has a null (-15 dBi) towards the boresight at its second resonance.

In order to investigate this behaviour, we compared the current distributions on the first-iteration MSR antenna geometries (aspect ratio = 0.8) with a square ring antenna. Simulation results at the respective second resonant frequencies are shown in Fig. 6. The directions of currents at these locations are indicated with arrows shown by the side. These indicate that two of the current maximas of the MSR geometry occur on the vertical segments and the other two on the horizontal segments. The resultant polarisations of their respective radiations would be orthogonal and hence a peak is observed in the boresight direction for these geometries. Further, it may now be easy to visualise that when the aspect ratio is reduced, the locations of the current maximas on the vertical segments of the MSR geometry would move towards the corners, ultimately reaching (*a*) for aspect ratio = 0.

4 Experimental validation

Various antennas with MSR geometries shown in Fig. 3 were fabricated for comparison with a square ring antenna. All these antennas were made using microwave substrate (RO-3003) from Rogers Corp., USA, using standard printed circuit fabrication techniques. An aluminium ground plane of dimensions 20 cm × 20 cm supports this structure. The transmission line is fed using a probe-type SMA connector. The fabricated antennas are tested using a vector network analyser. The measured return loss characteristics are shown in Fig. 7.

These fabricated antennas are characterised in a microwave anechoic chamber for their radiation patterns. As shown in Fig. 8, the radiation pattern at the second resonance of the square ring shows a null towards boresight, whereas antennas with MSR geometry show radiations comparable with those at the primary resonance frequency. As expected, the selected Minkwoski-square ring antennas have similar radiation patterns at both frequencies and hence behave as dual-frequency antennas.

5 Conclusions

This study showed that by appropriately choosing the fractal properties one can design a dual-frequency microstrip ring antenna using Minkowski curves. As three sides of a square ring antenna were replaced with these fractal geometries, the overall area can be reduced. However, as these fractal geometries were used, the resonant frequency differed from the values corresponding to the mean perimeter. It has been shown that the slope of variation in resonant frequency against the aspect ratio is approximately the same in all cases studied.

Based on the parametric studies presented here, one can observe that such dual-frequency characteristics of the antenna tend to improve as the geometry approaches self-similarity. The geometries for such a dual-frequency antenna may be chosen such that a pair of peaks in the current distribution at the second resonant frequency moves away from the geometrical symmetry locations. Hence a similar effect cannot be ruled out for non-fractal geometries. However, results presented here indicate a similar behaviour for the first- and second-iteration fractal geometries. Prototype antennas were fabricated with these geometries and the experimental results agreed with numerical simulations.

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