A New Fractal Microstrip Bandpass Filter Design Based on Dual-Mode Square Ring Resonator for Wireless Communication Systems

A new fractal design scheme has been introduced to generate dual-mode microstrip bandpass filter designs with miniaturized sizes for wireless applications. The presented fractal scheme is based on the Koch pre-fractal geometry applied to the conventional dual-mode microstrip square ring resonator as an initiator in the fractal generation process. The space-filling property that the proposed structures possesses, was found to produce reduced size symmetrical structures corresponding to the successive iteration levels. In addition, self-similarity of the whole structure about its diagonal, at any iteration level, enables it to produce the two degenerate modes which can then be coupled using a proper perturbation technique. These filter designs are of sizes suitable for use in modern wireless communication systems. The performance of each of the generated bandpass filter structures up to the 2nd iteration has been analyzed using a method of moments (MoM) based software IE3D, which is widely adopted in microwave research and industry. Results show that these filters possess good transmission and return loss characteristics, besides the miniaturized sizes gained; meeting the design specifications of most of wireless communication systems.

Keywords: Microstrip filter, Koch fractal, filter miniaturization, dual-mode resonator

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1. Introduction

Fractal geometry has found extensive applications in almost all the fields of science, technology and art, since the pioneering work of Mandelbrot about three decades ago [1]. Among these fields are the physical and engineering applications. In electromagnetics, fractal geometry has been applied widely in the fields of antenna and passive microwave circuit design, due the fantastic results gained in the miniaturization and the performance as well.

Two common properties; space-filling and self-similarity, that fractal geometries have, make them different from Euclidean geometries. It has been shown that the self-similarity property of fractal shapes can be successfully applied to the design of multi-band fractal antennas, such as the Sierpinski gasket antenna [2], while the space-filling property of fractals can be utilized to reduce antenna size [3]. Fractal curves are well known for their unique space-filling properties. Research results showed that, due to the increase of the overall length of the microstrip line on a given substrate area as well as to the specific line geometry, using fractal curves reduces resonant frequency of microstrip resonators, and gives narrow resonant peaks. Most of the research efforts has been devoted to antenna applications. In passive microwave design, the research is still limited to few works and is slowly growing [2,3]. Among the earliest predictions of the use of fractals in the design and fabrication of filters is that of Yordanov et al., [4]. Their predictions are based on their investigation of Cantor fractal geometry.

However, recent development in wireless communication systems has presented new challenges to design and production of high-quality miniaturized components. These challenges stimulate microwave circuits designers and antenna designers to seek out for solutions by investigating different fractal geometries [5-9]. Hilbert's fractal curve has been used as a defected ground structure in the design of a microstrip lowpass filter operating at the L-band microwave frequency [5]. Sierpinski fractal geometry has been used in the implementation of a complementary split ring resonator [6]. Split ring geometry using square Sierpinski fractal curves has been proposed to reduce resonant frequency of the structure and achieve improved frequency selectivity in the resonator.
performance [8]. Koch fractal shape is applied to mm-wave microstrip bandpass filters integrated on a high-resistivity Si substrate [9]. Results showed that the 2nd harmonic of fractal shape filters can be suppressed as the fractal factor increases, while maintaining the physical size of the resulting filter design [7]. Minkowski-like prefractal geometry has been used successfully in producing high performance miniaturized dual-mode microstrip bandpass filters [2,3].

In this paper, a new fractal scheme, based on applying Koch pre-fractal curve to the conventional microstrip dual-mode square ring resonator, is used to produce successful miniaturized design structures for the dual-mode microstrip bandpass filter. The resulting dual-mode bandpass filters are supposed to have noticeably miniaturized sizes with adequate reflection and transmission responses.

2. The Proposed Fractal Scheme

The square ring with a side length $L_0$, Fig. (1b), is considered as the starting pattern for the proposed bandpass filter as a fractal. From this starting pattern, each of its four sides is replaced by what is called the generator structure shown in Fig. (1a). To demonstrate the fractal generation 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 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 bandpass filter at resonance. It has been found that [4,5]:

$$P_n = \left(\frac{4}{3}\right)^n P_1$$

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 structure to increase its perimeter in the successive iterations was found very promising for examining its size reduction capability as a microstrip bandpass filter.

The basic idea to propose this fractal technique to generate a miniaturized microstrip bandpass filter structures has been borrowed from the successful application of such a technique in the microstrip antenna design, where compact size and multi-band behavior have been produced due to the space-filling and self-similarity properties of the resulting microstrip fractal antenna design [2,3,10-12].

Fig. (1) The generation process of the Minkowski-like prefractal structure; (a) the generator, (b) the square ring resonator, (c) the 1st iteration, (d) the 2nd iteration, and (e) the 3rd iteration

It has been concluded in antenna design, that the number of generating iterations required to make use of the benefits of miniaturization is only few before the additional complexities become indistinguishable [10,13]. This is true in this field, since the antenna aperture when much reduced leads to less gain though the radiation performance is still attractive. However, this
cannot be as serious in the filter design unless practical limitations obscure its implementation due to fabrication tolerances.

In practice, shape modification of the resulting structures in Figs. (1c) and (1d) is a way to increase the surface current path length compared with that of the conventional square ring resonator, Fig. (1b); resulting in a reduced resonant frequency or a reduced resonator size, if the design frequency is to maintain. It is expected then, that the 2nd iteration, 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. An additional property that the presented scheme possesses is the symmetry of the whole structure in each of the iteration levels about its diagonal. This property is of special importance in the design of dual-mode loop resonators [14,15].

The length \( L_o \) of the conventional microstrip dual-mode square ring resonator has been determined using the classical design equations reported in the literature [14-16] for a specified operating frequency and given substrate properties. This length represents a slightly less than the quarter guided wavelength at its fundamental resonant frequency in the resonator.

Applying geometric transformation of the generating structure (Fig. 1a) on the square ring resonator (Fig. 1b), results in the filter structure depicted in (Fig. 1c). Similarly, successive bandpass filter shapes, corresponding to the subsequent iterations, can be produced as successive transformations are applied. At the \( n \)th iteration, the corresponding pre-fractal enclosing area, \( A_n \) has been found to be [4,5]:

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

(2)

The dimension of a fractal provides a description of how much it efficiently fills a space. It is a measure of the prominence of the irregularities when viewed at very small scales [17,18]. A dimension contains much information about the geometrical properties of a fractal. From the property of self-similarity, the fractal dimension \( D \) is defined as [17]:

\[
D = \frac{\log(N)}{\log(1/r)}
\]

(3)

where \( N \) is the total number of distinct copies and \( 1/r \) is the scale ratio.

To find the dimension of the Koch fractal curve, using Eq. (3), where \( N=4 \) segments and \( r=1/3 \), then the fractal dimension is \( D=1.26 \).

3. Filter Design

Three dual-mode microstrip bandpass filter structures corresponding to the zero, 1st, and 2nd iterations have been designed for the ISM band applications at a design frequency of 2.4GHz. It has been supposed that these filter structures have been etched using a substrate with a dielectric constant of 10.8 and thickness of 1.27mm. At first, the side length of the square ring resonator, \( L_o \), has to be calculated as [14-16]:

\[
L_o < \frac{\lambda_{go}}{4}
\]

(4)

where \( \lambda_{go} \) is the guided wavelength. Then the side length, \( L_n \), for the successive iterations can be calculated, based on the value of \( L_o \), using Eq. (1).

A small perturbation has been applied to each dual-mode resonator at a location that is assumed at a 45° offset from its two orthogonal modes. This perturbation, in the form of a small patch, is added to the square ring, and to the other subsequent iterations loop resonators. It should be mentioned that for coupling of the orthogonal modes, the perturbations could also take forms and locations other than the mentioned shape and position. But since the resulting resonators are characterized by their diagonal symmetry, this shape of perturbation is the most convenient to satisfy the required coupling. The effect of the perturbation size on the dual-mode ring resonator filter performance curves is not discussed here; since the main aim is to present a new technique for generating miniaturized bandpass filter design based on a fractal iteration process with acceptable performance. The dimensions of the perturbations of each filter must be tuned to satisfy the required filter performance, since the nature and the strength of the coupling between the two degenerate modes of the dual-mode resonator are mainly determined by the perturbation’s size and shape. However, extensive details about this subject can be found in [19,20].

The initially calculated value of \( L_o \) has to be adjusted to the design frequency, therefore, slight tuning of this value is necessary. Figures (2) and (3) show the layouts of the resulting dual-band bandpass filters and Table (1) summarizes the resulting side lengths and the satisfied size reduction percentages as compared with the conventional square ring resonator at the design frequency. It is expected that the 3rd and the 4th iterations bandpass filter structures may satisfy further size reductions of about 82% and 89% respectively, if the fabrication tolerances permit implementation.
4. Performance Evaluation

Filter structures, depicted in Figs. (2) and (4), have been modeled and analyzed at an operating frequency, in the ISM band, of 2.4GHz using the IE3D electromagnetic simulator from Zeland Software Inc. [21]. This simulator performs electromagnetic analysis using the method of moments (MoM). The corresponding simulation results of return loss and transmission responses of these filters are shown in Figs. (5) and (7), respectively.

Table (1) Summary of the dimensions and the size reduction percentages of the pre-fractal filters up to 4th iteration at a design frequency of 2.45GHz

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Ls (mm)</th>
<th>Size Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square patch (0 iteration)</td>
<td>41.35</td>
<td>-</td>
</tr>
<tr>
<td>1st iteration</td>
<td>31.01</td>
<td>43.75</td>
</tr>
<tr>
<td>2nd iteration</td>
<td>23.25</td>
<td>68.38</td>
</tr>
<tr>
<td>3rd iteration</td>
<td>17.44</td>
<td>82.21</td>
</tr>
<tr>
<td>4th iteration</td>
<td>13.08</td>
<td>89.98</td>
</tr>
</tbody>
</table>

It is implied from these figures that the resulting pre-fractal bandpass filters offer adequate performance curves as those for the conventional dual-mode square ring resonator, Fig. (5). As can be seen, all of the filter responses show two transmission zeros symmetrically located around the design frequency.

However, these responses and their consequent poles and zeros could be, to a certain extent, controlled through the variation of the perturbation dimensions and/or the input/output coupling used. Figures (8-10) show the current density patterns using the EM simulator for 2nd iteration dual-mode microstrip bandpass filter.
the design frequency and other two frequencies around it.

It clear from these figures that only at the design frequency the two degenerate modes are excited and coupled to each other leading to the required filter performance, while at the other two frequencies, no degenerate modes are excited at all as expected. In these figures, the same color code is used as an indication for the current densities.

5. Conclusions

A fractal design scheme has been presented in this paper, as a new technique for microstrip bandpass filter design based on dual-mode square ring resonator. Due to the space-filling property of the presented fractal possess, the resulting filter designs have proven to be more compact in size as the iteration process goes on. This makes them appropriate for use in modern mobile communication systems, where the miniaturized size becomes a critical requirement.

Up to the 2nd iteration, microstrip bandpass filters have been designed according to the presented technique and analyzed using the method of moments (MoM) at the ISM frequency band. Simulation results show that these filters possess reasonable return loss and transmission performance responses.

Microstrip bandpass filters designs based on the 1st and 2nd iterations have shown size reductions of about 43% and 68% as compared with the conventional microstrip square ring bandpass filter designed at the same frequency and using the same substrate material. As the practical fabrication tolerances may permit, it is expected that the 3rd iteration and 4th iteration filter structures will offer further size reductions of about 82% and 89% respectively, as predicted by the presented fractal scheme.

The proposed technique can be generalized, as a flexible design tool, for compact microstrip bandpass filters for a wide variety of wireless communication systems.

References