Design of Miniaturized Dual-Mode Microstrip Resonator Bandpass Filters for Modern Wireless Applications

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Abstract—The design of a new compact size dual-mode microstrip resonator filter is presented in this paper, as a candidate for use in modern wireless applications. The proposed resonator structure is a result of applying two reduction techniques to the conventional dual-mode microstrip square patch resonator. The edges of the conventional square patch have been replaced by 1st and 2nd iteration Koch pre-fractal curves. The proposed resonator filters have been designed for ISM band applications, at 2.4 GHz, using a substrate with relative dielectric constant of 10.8 and thickness of 1.27 mm. The resulting microstrip dual-mode resonators have been found to possess size reductions of about 24% and 27% respectively, as compared with the conventional square patch dual-mode resonator using the same substrate and designed at the same frequency. Moreover, these resonators have been further reduced in size by inserting a crossed-slot pattern in the respective patch structures. In this case, the corresponding resonators offer size reductions of about 61% and 64%, as compared with the conventional square patch dual-mode resonator. Modeling and performance evaluation of the presented resonator structures have been carried out using a method of moments based IE3D EM simulator. Simulation results show that the proposed filters have acceptable return loss and transmission responses besides the miniaturized size gained.

Keywords: Dual-mode resonator, microwave resonator miniaturization, Koch fractal geometry, microstrip bandpass filter

I. INTRODUCTION

Recent developments in wireless communication systems have presented new challenges to design and produce high-quality miniaturized passive microwave components. These challenges stimulate microwave circuits designers and antennas designers to seek out for solutions by investigating different fractal geometries [1-3]. Since the pioneer’s work of Mandelbrot [4], a wide variety of applications for fractal has been found in many areas of science and engineering. One such area is fractal electrodynamics in which fractal geometry is combined with electromagnetic theory for the purpose of investigating a new class of radiation, propagation, and scattering problems [5]. One of the most promising areas of fractal electrodynamics research is its application to the passive microwave circuit design.

Fractal geometries have two common properties; space-filling and self-similarity, making them different from Euclidean geometries. Fractal curves are well known for their unique space-filling properties. It has been shown that the self-similarity and space-filling properties of fractal shapes, such as Minkowski and Koch fractal curves, can be successfully applied to the design of miniaturized microstrip dual-mode ring bandpass filters [6,7]. Space-filling property of many fractals can be utilized to realize reduced size single-mode microstrip bandpass filters [8,9].

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, the use of fractal curves reduces resonant
frequency of microstrip resonators, and gives narrow resonant peaks. Most of the research efforts has been devoted to the antenna applications. In passive microwave circuit design, the research is still limited to few works and is slowly growing [6]. Among the earliest predictions of the use of fractals in the design and fabrication of filters is that of [10]. Their predictions are based on their investigation of Cantor fractal geometry.

In this paper, new miniaturized structures for the design of dual-mode resonator microstrip patch bandpass filters are presented. The proposed size reduction technique is based on applying Koch pre-fractal curves of the first and second iterations, together with a crossed-slot pattern embedded inside the patch structure itself, to the conventional dual-mode microstrip square patch resonator. The resulting microstrip bandpass filters are supposed to have noticeably miniaturized sizes with adequate reflection and transmission responses, making them suitable for use in the compact size modern wireless applications.

II. THE FILTER STRUCTURE GENERATION PROCESS

Two miniaturization techniques have been simultaneously applied to the conventional dual-mode microstrip patch resonator in order to produce the proposed compact bandpass filters. The first miniaturization technique is to apply Koch fractal curve geometry to the edges of the square patch resonator. In this step, the square patch with a side length $L_o$, 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. After that, the generator is scaled, 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 has been carried out an infinite number of times [11]. The resulting pre-fractal structure has the characteristic that the perimeter increases to infinity while maintaining the volume occupied.

The increase in length decreases the required volume occupied for the pre-fractal bandpass filter at resonance. It has been found that [7]:

$$P_r = \left(\frac{4}{3}\right) P_i,$$  

(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 triggering for examining its size reduction capability as a dual-mode microstrip bandpass filter.

The basic idea to propose this fractal technique to design 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 [12].

In practice, shape modification of the resulting structures in Fig. 1c and 1d is a way to increase the surface current path length compared with that of the conventional square patch resonator, Fig. 1b. This leads to a reduced resonant frequency or a reduced resonator size, if the design frequency is to be maintained. 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 [13,14].

The length \( L_o \) of the conventional microstrip dual-mode square patch resonator has been determined using the classical design equations reported in the literatures [13,14], for a specified operating frequency and given substrate properties. This length represents a slightly less than half the guided wavelength at its fundamental resonant frequency in the resonator. Applying geometric transformation of the generating structure (Fig.1a) on the square patch resonator (Fig.1b), results in filter structure depicted in Fig.1c. Similarly successive bandpass filter shapes, corresponding to the subsequent iterations, could be produced as successive transformations have been applied. So far, the first miniature-ization step has been supposed to be completed. The second miniaturization step, according to the proposed technique, is to implement crossed-slot patterns inside the Koch fractal based microstrip patch resonator structures resulting from the previous step. The final filter structures are shown in Fig. 2.

![Fig.2 The layouts of the modeled dual-mode microstrip patch bandpass filters with resonators based on (a) the first iteration fractal Koch curve patch, (b) the first iteration fractal Koch patch curve and a crossed-slot structure, (c) the second iteration fractal Koch curve patch, and (d) the second iteration fractal Koch patch curve and a crossed-slot structure.](image)

### III. The Proposed Filter Design

Two sets of microstrip dual-mode bandpass patch filter structures have to be designed, modeled, and the corresponding performance has to be assessed. The first set consists of three bandpass filters, with their microstrip patch resonators are based on the
conventional square, the first iteration Koch fractal curve, and the second iteration Koch fractal curve. The second set of filters is the same as those prescribed in the first set, but with crossed-slot structures implemented in their respective microstrip patch resonators. Filters in both sets have been designed for the ISM band applications at 2.4 GHz. It has been supposed that these filter structures have been etched using a substrate with a relative dielectric constant of 10.8 and thickness of 1.27 mm. The dual-mode coupling of the two degenerate modes of all filters is achieved via capacitive coupling with input/output 50 ohms microstrip transmission lines.

At first, the side length of the square microstrip patch resonator, $L_o$, has to be calculated as [13,14].

$$L_o \leq \frac{\lambda}{2}$$

(2)

where $\lambda$ is the guided wavelength, given by [15]:

$$\lambda = \frac{\lambda_o}{\sqrt{\varepsilon_{re}}}$$

(3)

where $\lambda_o$ is operating wavelength at the design frequency, and $\varepsilon_{re}$ is the effective dielectric constant given by [15]:

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left(1 + 12 \frac{h}{w}\right)^{-0.5}$$

(4)

where $h$ is the substrate thickness and $w$ is the width of the patch microstrip structure. However the effective dielectric constant has been calculated using the adopted electromagnetic software. Then the side length, $L_n$, for the successive iterations can be calculated, based on the value of $L_o$, using Equ. (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 is in the form of a small patch is added to the square patch, and to the other subsequent iterations patch 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 patch resonator filter performance curves should not be discussed this paper; since the main aim is to present a new technique for generating miniaturized dual-mode bandpass filter design based on a fractal iteration process and embedded crossed-slot structure with acceptable performance. The dimensions of the perturbations of each filter have to 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 [16,17].

The initially calculated value of $L_o$ has to be adjusted to the design frequency, therefore slight tuning of this value is necessary. The crossed-slot structures have then cut in the microstrip patch resonators. The length and the width of the inserted crossed slot pattern have to be optimized in order to reach the two degenerated modes at the design frequency. It is important to mention here that, in this case, there is no need to add the prescribed perturbation structure. Instead, a slight difference in the arms of the crossed slot length will stand for the required perturbation. Figure 2 shows the layouts of the resulting dual-slot microstrip patch bandpass filters.

The resonating side length of the square patch resonator, Fig. 1b, has been found to be of about 18.4 mm using the prescribed substrate. This length represents slightly less than half the guided
wavelength, which is in good agreement with the theoretical predictions expected by Equs. (2-4). Inserting the crossed slot structure in this resonator, the new resonating side length has been found to be of about 12.15 mm with slot length and width of 14.2 mm and 0.35 mm respectively.

In the other hand, the resonating side length of the patch resonator based on first iteration Koch fractal geometry, Fig. 1c, has been found to be of about 16.5 mm, while the resonating length with crossed slot structure inserted in this resonator, is of about 11.60 mm with slot length and width of 12.9 mm and 0.35 mm respectively. Furthermore, the resonating side length of the patch resonator based on the second iteration Koch fractal geometry, Fig. 1d, has been found to be of about 15.78 mm, while the resonating length with crossed slot structure inserted in this resonator, is of about 11.12 mm with slot length and width of 12.1 mm and 0.35 mm respectively. The crossed slot structures, embedded in the patch resonators, have a considerable impact in size reduction of these resonators as compared with those which have no slots in their structures. The apparent reason for this is that these slots provide additional paths of the surface currents constituting the coupled degenerating modes, as will be shown later.

Table (1) summarizes the resulting side lengths and the size reduction percentages as compared with the conventional microstrip square patch resonator at the design frequency. It is expected that microstrip dual-mode bandpass filters based on higher Koch fractal curve iterations may satisfy further size reductions, if the fabrication tolerances permit to be implemented.

IV. FILTER PERFORMANCE EVALUATION

Filter structures, depicted in Fig. 2, have been modeled and analyzed at an operating frequency, in the ISM band, of 2.4 GHz using the commercially available electromagnetic simulator IE3D from Zeland Software Inc. [18]. This simulator performs electromagnetic analysis using the method of moments (MoM).

![Graph 1](image1)

**Fig. 3** The return loss, $S_{11}$, response and the transmission loss, $S_{12}$, response of the dual-mode microstrip bandpass filter depicted in Fig. 2a.

![Graph 2](image2)

**Fig. 4** The return loss, $S_{11}$, response and the transmission loss, $S_{12}$, response of the dual-mode microstrip bandpass filter depicted in Fig. 2b.

The corresponding simulation results of return loss and transmission responses of these filters are shown in Figs. 3 - 6 respectively. It is implied from these figures that the resulting pre-fractal bandpass filters, with and without crossed-slot structures,
offer adequate performance curves as those for the conventional dual-mode square patch resonator. 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.

Furthermore, Figs. 4 and 6 corresponding to the filters with crossed-slots imply that these filters offer broader fractional bandwidths as compared with their counterparts without slots responses depicted in Figs. 3 and 5.
Examining Figs. 4 and 6, the realized fractional bandwidths by the modeled filter with crossed-slots are 2.73% and 2.58% respectively, while the fractional bandwidths realized by the filter without crossed-slot, Figs. 3 and 5, are 1.44% and 1.29% respectively. As a rough estimate, the filters with slots possess twice the fractional bandwidths offered by those without slot.

Figure (7) illustrates the current density patterns using the EM simulator for the dual-mode microstrip bandpass filter, based on the second iteration Koch fractal curve microstrip patch resonator depicted in Fig. 2d, at the design frequency and other two frequencies around it.

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Resonator Side Length (mm)</th>
<th>Size Reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square patch</td>
<td>Without slot</td>
<td>18.40</td>
</tr>
<tr>
<td></td>
<td>With slot</td>
<td>12.15</td>
</tr>
<tr>
<td>2nd iteration</td>
<td>Without slot</td>
<td>16.05</td>
</tr>
<tr>
<td></td>
<td>With slot</td>
<td>11.55</td>
</tr>
<tr>
<td>1st iteration</td>
<td>Without slot</td>
<td>15.78</td>
</tr>
<tr>
<td></td>
<td>With slot</td>
<td>11.15</td>
</tr>
</tbody>
</table>

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 as expected at all. In these figures, the same color code is used as an indication for the surface current densities. It is clear that maximum current densities occur at the resonant frequency, as Fig. 7b implies. It is worth to note the higher values of the surface current densities around the embedded crossed-slot structure, which considerably contribute to resonator size reduction.

The prescribed filter designs can easily be scaled to other frequencies required for other wireless communication systems. In such a case, the resulting new filter will be of larger or smaller in size according to the frequency requirements of the frequency.
specified applications. However, this process is no longer linear.

V. CONCLUSIONS

A new technique for miniaturization of microstrip bandpass filter design based on dual-mode square patch resonator has been presented in this paper. According to the proposed technique, miniaturization has been achieved by applying both Koch fractal geometry and crossed slot structure to the conventional square patch microstrip resonator.

Microstrip dual-mode bandpass filters based on the first and second iteration Koch fractal curves, with and without crossed-slot structures, have been designed and analyzed using the method of moments (MoM) at the ISM band.

Microstrip bandpass filter design, based on the first iteration Koch fractal curve, without crossed slot, has shown to offer size reduction of about 24%, as compared with the conventional microstrip square patch bandpass filter designed at the same frequency and using the same substrate material. Adding the slot structure to this filter, results in a further miniaturized size reduction of about 61%. The resulting size reduction percentages corresponding to filters based on the second iteration Koch fractal curves are 27% and 64% respectively. Simulation results show that these filters possess reasonable return loss and transmission performance responses. Moreover, the modeled bandpass filters with crossed-slot structure have approximately twice the fractional bandwidths offered by those without slots. As the practical fabrication tolerances may permit, it is expected that filter structures based on higher iterations will offer further size reduction percentages, 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. Besides the reduced size gained, the proposed resonator offers acceptable return loss and transmission loss performance with symmetrical responses about the design frequency.

More research has to be conducted to explore the validity of applying the higher iterations on the proposed filter, in an attempt to realize more size reduction. It is hopeful that proposed resonator finds its place for use in miniaturized modern wireless applications.

REFERENCES

and Electromagnetic Compatibility, MAPE 2009, Beijing, China.


