A Compact Triple Band BSF Design Based on Minkowski Fractal Geometry

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January 18, 2016
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Abstract- In this paper, Minkowski fractal based open-loop resonators are adopted to design triple band microstrip bandstop filters (BSFs). The suggested filter structures are primarily based on that of the conventional open-loop rectangular microstrip resonators. The resonators of the proposed BSF structure are made in the form of Minkowski fractal geometry with different iteration levels. Many filter structures have been modeled, and their performances have been evaluated using the commercially available EM simulator, Sonnet. Each of the modeled filter structures contains two pairs of open loop fractal based resonators with different iteration levels. The lower frequency bandstop performance is attributed to the resonators with higher iteration level while the higher frequency bandstop performance is due to the resonators with lower iteration levels. Simulation results for the proposed microstrip filters have confirmed the validity to realize compact multiband narrow-stopband microstrip filters. Measured results of a fabricated filter prototype are found to be in reasonable agreement with those predicted by numerical computation. The results presented show that the proposed fractal based resonators can be used to construct compact multiband filters with narrow stopbands.

1. INTRODUCTION

Over the last 25 years, self-similarity and fractals have opened an important way of finding solutions for microwave antennas and passive circuit design. Applying various fractal geometries to antennas, resonators, and related structures, the resulting benefits include, among many, wider bandwidths, smaller sizes, and better performance. Fractals also provide a new generation of optimized design tools, first used successfully in antennas, but it has been found to be applicable in a general fashion [1].

The application of various fractal geometries to the conventional ring resonators has been successfully adopted in the design of compact microwave microstrip filters and planar circuits. In this context, split rings using square Sierpinski fractal curves have been proposed to reduce the resonant frequency of the structure and achieve improved frequency selectivity in the resonator performance [2]. Based on the conventional square patch, a dual-mode microstrip bandpass filter (BPF) has been designed adopting Sierpinski fractal geometry [3]. High performance miniaturized dual-mode microstrip BPFs have been produced by the successful application of Peano fractal geometries to the conventional square open-ring resonators [4-7]. Furthermore, other fractal geometries, such as Hilbert, Moore and Koch have been also adopted to design miniaturized microstrip bandpass
filters [9-11]. On the other hand, Minkowski fractal based microstrip resonators are successfully applied to produce compact dual-mode microstrip BPFs [11-17]. However, research works dealt with the application of fractal based structures to design microstrip BSFs have been seldom reported in the literature [7, 8]. A Peano fractal shaped open stub microstrip resonator has been proposed to reduce the second harmonics of a dual-mode BPF [7]. Two pairs of Peano fractal based resonators have been suggested to design a compact size dual-band microstrip BSF [8]. The dual-band BSF performance is attributed to the use of two pairs of Peano fractal based resonators, with different enclosed lengths.

In this paper, a compact triple band microstrip BSF with Minkowski fractal based open-loop resonators is presented. Different iteration levels have been applied to open-loop microstrip resonators that the proposed filter constitutes. This will result in compact microstrip BSFs with single, dual and triple band stopband responses.

2. THE PROPOSED FILTER CONFIGURATION

The proposed BSF structure represents an improvement of that of the conventional BSF with open-loop square ring resonators, shown in Fig. 1 [18], as a starting step. In this filter, the resonant frequency of the stopband is dependent on the perimeter of the open-loop square ring resonator. The proposed configuration of the presented filter will constitute of open-loop resonators each with different iteration level of Minkowski-like pre-fractal structures depicted in Fig. 2. Each resonator will create its band reject since each has a different perimeter. Practically, the fractal based shape modification of the filter structure shown in Fig. 1 is a way to increase the surface current path length; resulting in a reduced resonant frequency or a reduced resonator size, if the design frequency is to be maintained [12].

![Figure 1: The layout of the square open-loop microstrip BSF [18].](image)

![Figure 2: The steps of growth of Minkowski-like pre-fractal geometry: (a) the generator, (b) the square ring, (c) the 1st iteration, and (d) the 2nd iteration [12].](image)

It is expected then; further miniaturization is possible when adopting ring structures with higher iteration levels as those depicted in Fig. 2(a-c). The increase of the modified ring lengths will decrease the required volume occupied for the fractal based bandpass filter at resonance. It has been found that the perimeter $P_n$ of the $n$th iteration pre-fractal structures is given by [8,17]:

$$P_n = \frac{4}{\sqrt{2}} P_{n-1}$$

where $P_0$ is the perimeter of the generator.
\[ P_n = \left(1 + 2 \frac{w_2}{L_o}\right) P_{n-1} \]  
(1)

where \( w_2 \) and \( L_o \) are as depicted in Fig. 2. It is obvious that, as \( n \) goes to infinity, the perimeter goes to infinity. However, the possible degree of miniaturization of the resulting filter structures considerably depends on the technology of the production of the filter prototype.

3. THE FILTER DESIGN

Based on Figs. 1 and 2, many fractal based microstrip BSFs could be developed; each with open-loop resonators having a different combination of Minkowski pre-fractal iteration levels starting from zero iteration (the square ring) up to the 2nd iteration level as depicted in Fig. 2. To save space, the results of only five filters are presented for demonstrative purposes. The first three filters among which are composed of similar open ring resonators as summarized in Table 1. They are designated as BSF-I, BSF-II, and BSF-III. The other two filters, designated as BSF-IV and BSF-V, are composed of more than one type of open-loop resonators. The first one consists of two types of resonators which are based on the first and the second iterations while the other filter is composed of three kinds of the resonator which are based on the zero, first and second iteration level. The latter filter structure, up to author’s knowledge, is a never-before-proposed filter design with three different resonator types.

Table (1): Comparison of the modeled filters

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Iteration Level</th>
<th>Resonant Frequency (GHz)</th>
<th>Bandwidth (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSF-I</td>
<td>Zero</td>
<td>3.15</td>
<td>140.0</td>
</tr>
<tr>
<td>BSF-II</td>
<td>First</td>
<td>2.15</td>
<td>40.0</td>
</tr>
<tr>
<td>BSF-III</td>
<td>Second</td>
<td>1.81</td>
<td>23.0</td>
</tr>
</tbody>
</table>

*All ring resonators have the same side lengths.

3. PERFORMANCE EVALUATION

The same substrate material, with relative dielectric constant of 10.8 and thickness of 1.27 mm, is adopted for all the modeled filters. The input/output ports have 50Ω characteristic impedance. The transmission line has a width of about 1.15 mm. In all of the modeled filters, the resonator side lengths have been kept with fixed side length of 6.0 mm. Based on this value and the resulting lowest resonant frequency, the miniaturization percentage will be calculated for each filter structure.

The simulated \( S_{11} \) and \( S_{21} \) responses of the modeled BSF-I are shown in Fig. 3. A single resonance is observed at 3.15 GHz throughout the swept frequency range 2-4 GHz. In terms of the corresponding guided wavelength \( \lambda_{g1} \), the side length of the ring resonators represent about 0.088 \( \lambda_{g1} \):

\[ \lambda_g = \frac{\lambda_{g1}}{\sqrt{\varepsilon_{eff}}} \]  
(2)
where $\varepsilon_{\text{eff}}$ is the effective dielectric constant that can be calculated by empirical expressions reported in the literature [16]. However, most of the commercially available EM simulators can perform a direct calculation of both $\lambda_g$ and $\varepsilon_{\text{eff}}$, for given substrate parameters and the operating frequency. For the present case, $\lambda_g$ has been found at the design frequency to be 67.57 mm. Simulated $S_{11}$ and $S_{21}$ responses of the modeled BSF-II and BSF-III are depicted in Figs. 4 and 5 respectively. Again, single resonances have been observed but with frequencies that are lower than that offered by BSF-I. This is attributed to the extra embedded lengths of the fractal based ring resonators.

![Graph](image)

Figure 3: Simulated $S_{11}$ and $S_{21}$ responses of the proposed BSF-I based on the zero iteration open-loop resonators.

![Graph](image)

Figure 4: Simulated $S_{11}$ and $S_{21}$ responses of the proposed BSF-II based on the 1st iteration fractal based open-loop resonators.

The resonances offered by the modeled BSF-II and BSF-III are at about 2.15 GHz and 1.81 GHz, respectively, throughout the swept frequency range 1-3 GHz. In terms of the corresponding guided wavelengths $\lambda_{g_2}$ and $\lambda_{g_3}$, the side lengths of the ring resonators represent about 0.113 $\lambda_{g_2}$ and 0.096 $\lambda_{g_3}$. The BSF-IV structure is composed of two types of fractal based open ring resonators; based on 1st and 2nd iterations. The corresponding return loss response of this filter, as shown in Fig. 6, with two stopbands centered at about 1.74 and 2.12 GHz with corresponding bandwidths of about 13.0 and 38.0 MHz. The lower resonance is attributed to the 2nd iteration ring resonator while the upper resonance is attributed to the 1st iteration ring resonator.
As it is implied in Fig. 7, the BSF-V has $S_{11}$ and $S_{21}$ responses with three stopbands centered at 1.68, 2.07, and 3.05 GHz with corresponding bandwidths of about 9.0, 20.0, and 50.0 MHz. These resonances are attributed by the 2nd iteration, 1st iteration, and the zero iteration based resonators respectively as longer perimeter results in lower resonant frequency. An interesting result, when using different fractal based resonators in the proposed filter structures as in BSF-IV and BSF-V, is that each resonator type behaves as if it exists alone and its resonance. As a consequence, the resulting filter response is the combination of the individual responses.
attributed by the different resonators. Accordingly, the response of the BSF-V shown in Fig. 7 can be thought as the combination of the responses of the BSF-I, BSF-II, and BSF-III depicted in Figs. 3-6 respectively. This result can be further interpreted with the aid of the current distributions on the surface of the BSF-V at different in-band and out-of-band frequencies as demonstrated in Fig. 8. The first resonant frequency, at 1.68 GHz, is caused by the open loop ring resonator based on the 2nd iteration. The filter works as if this resonator performs alone regardless of the existence of the other resonators. The same conclusion can be noticed about the other two resonances, occur at 2.07 and 3.05 GHz, and their correlation to the ring resonators based on the 1st and zero iterations respectively.

![Current Distributions](image)

**Figure 8:** Simulated surface current distribution of the proposed triple band BSF at different in-band and out-of-band frequencies.

As stated earlier, all the modeled filters are designed with equal side length resonators. As a consequence, the resulting stopbands of the BSF-V depicted in Fig. 7, appear at frequency ranges of limited practical importance. However, since the resulting filter performance is the combination of the individual responses attributed by the different resonators, the BSF-V has been redesigned to offer useful stopbands of practical importance. This can be achieved by dimension scaling of the various resonators to produce stopbands at the required frequencies. The proposed filter has been required to produce stopbands at 2.4, 3.4 and 5.0 GHz, using a substrate of 10.8 relative dielectric constant and 1.27 mm thickness. The resulting filter has resonators with different side lengths of about 4.45, 3.88 and 3.86 mm, which correspond to the 2nd, 1st, and zero iteration structures.

A prototype of this filter has been fabricated on the same substrate. Figure 9 shows a photo of the fabricated prototype. Measured and Simulated $S_{11}$ and $S_{12}$ responses of the fabricated filter are shown in Figs. 10 and 11 respectively. Reasonable agreement between measured and simulated results can be observed. The slight differences are attributed to the dimensional fabrication tolerances and the conductor losses that are not taken into account.
In summary, the proposed filter design seems attractive in that it offers a triple stopband response with flexible resonant frequency ratios. It needs only to modify an individual resonator dimension to tune its resonant frequency keeping other resonators unchanged. In this context, the proposed filter overperforms many similar filter designs, such as those reported in the literature [20-24], where the resonant frequencies are highly dependent on each other, and it is difficult to tune a particular resonant frequency without affecting the others. It is only possible to tune the resonant frequencies together by the dimension scaling of the whole filter structure.

5. CONCLUSIONS
A compact size triple band microstrip BSF, using fractal based open ring resonators, has been presented in this paper. Results show that the application of higher fractal iteration levels results in more filter miniaturization. Furthermore, dual-band and multiband BSFs can be designed using fractal based open loop ring resonators with different iteration levels in the same filter structure. However, the realization of BSFs with higher miniaturization depends on the limitations imposed by fabrication technique adopted to produce the filter prototype. The proposed filter design offers a flexible triple bandstop response with the possibility to tune any of the resonant bands by the dimension scaling of the corresponding resonator producing it. To a certain extent, the resonant frequency ratio can be varied according to various practical requirements.

REFERENCES


