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Fractally Generated Microstrip Bandpass Filter Designs Based on Dual-Mode Square Ring Resonator for Wireless Communication Systems

Jawad K. Ali

Department of Electrical and Electronic Engineering/ University of Technology
P.O. Box 35239, Baghdad, Iraq, Email: jawengin@yahoo.com

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Abstract

A novel fractal design scheme has been introduced in this paper to generate microstrip bandpass filter designs with miniaturized sizes for wireless applications. The presented fractal scheme is based on Minkowski-like prefractal geometry. The space-filling property and self-similarity of this fractal geometry has found to produce reduced size symmetrical structures corresponding to the successive iteration levels. The resulting filter designs are with 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 meeting the design specifications of most of wireless communication systems.

Keywords: Microstrip bandpass filter (BPF), filter miniaturization, dual-mode resonator, square ring resonator.

1. Introduction

Since the pioneer work of Mandelbrot [1], the fractal geometry has found extensive applications in almost all the fields of science. 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 performance as well.

Different from Euclidean geometries, fractal geometries have two common properties, space-filling and self-similarity. 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, while the space-filling property of fractals can be utilized to reduce antenna size. 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 narrows resonant peaks.

Most of the research efforts has been devoted to the antenna applications. In passive microwave design, the research is still limited to few works and is slowly growing. Among the earliest predictions of the use of fractals in the design and fabrication of filters is that of Yordanov et.al, [2]. 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 produce high-quality miniaturized components. These challenges stimulate microwave circuits designers and antennas designers to seek out for solutions by investigating different fractal geometries [3-7].

Hilbert 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 [3].

Sierpinski fractal geometry has been used in the implementation of a complementary split ring resonator [4]. 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.

Koch fractal shape is applied to mm-wave microstrip band pass filters integrated on a high-resistivity Si substrate. 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 [5].

In this paper, a new fractal scheme, based on Minkowski-like prefractal geometry, is presented to produce successive design geometries for the dual-mode microstrip bandpass filter based on the conventional dual-mode square ring resonator as a starting step. The resulting filters are supposed to have miniaturized sizes with adequate reflection and transmission responses.

2. The Proposed Fractal Scheme

The starting pattern for the proposed bandpass filter as a fractal is the square ring with a side length L_o, Fig1b. From this starting pattern, each of its four sides is replaced by what is called the generator structure shown in Fig1a. 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 has been carried out an infinite number of times. The generator is composed of five segments .The middle segment, w_1, is chosen such that it is with shorter length than the two end segments. The other two vertical segments are tuned to adjust the overall perimeter of the fractal length. This tuning length is called the indentation width, w_2 [8]. 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:

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

where P_n is the perimeter of the nth iteration pre-fractal and a_2 is the ratio w_2/L_o. 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 bandpass filter.

The basic idea to propose a 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 [9,10]. 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 [8.9]. This is right 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.

Practically, 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 maintained. The space filling geometry and the self similarity that the 1st iteration structure in Fig. 1c possesses, make it analogous to the modified square microstrip antenna reported in the literature [11,12]. 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 ring resonator has been determined using the classical design equations reported in the literatures [13-15] for a specified value of the operating frequency and given substrate properties. This length represents a slightly less than quarter the guided wavelength at its fundamental resonant frequency in the resonator.

As shown in Fig. 1, applying geometric transformation of the generating structure (Fig. 1a) on the square ring resonator (Fig. 1b), results in filter structure depicted in (Fig. 1c). Similarly successive bandpass filter shapes, corresponding to the following iterations can be produced as successive transformations have been applied. At the n^{th} iteration, the corresponding filter side length, L_n has been found to be:

$$L_n = (0.6)^{\frac{n}{2}} L_o \qquad \ldots(2)$$

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

$$A_n = (0.6)^n A_o \qquad \ldots(3)$$

where A_o is the area occupied by the conventional square ring resonator.

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 [16, 17]. A dimension contains much information about the geometrical properties of a fractal. According to Falconer [16], since the generator used to develop the proposed fractal structure involves similarity transformations of more than one ratio; a_1 and a_2, the dimension of the 2^{nd} iteration structure can be obtained from the solution of the following equation:

$$2\left(\frac{1}{2}(1-a_1)\right)^D + 2a_2{}^D + a_1{}^D = 1 \qquad \ldots(4)$$

where D, represents the dimension, a_1 is the ratio w_1/L_o, and a_2 is as defined earlier. Then the dimension of the proposed structure, according to Equ (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. It is worth to mention here, the dimension of traditional Minkowski island fractal, according to Equ. (4), is equal to 1.465, where in such a case, a_1 and a_2 are both equal to one-third.

3. Filter Designs

Three microstrip dual-mode bandpass filter structures corresponding to the zero, 1^{st}, and the 2^{nd} iterations have been designed for the ISM band applications at the design frequency of 2.4 GHz. It has been supposed that these filter structures have been etched using a substrate with a dielectric constant of 10.8 and thickness of 1.27 mm. At first, the side length of the square ring resonator, L_o, has to be calculated as [13-15]:

$$L_o < \frac{\lambda_{go}}{4} \qquad \ldots(5)$$

where λ_{go} is the guided wavelength .Then the side length, L_n, for the successive iterations can be calculated, based on the value of L_n, using Eqn (2).

Note that 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 ring, and the other subsequent iterations loop resonators. It should be mentioned that for coupling of the orthogonal modes, the perturbations could also take forms other than this shape. 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 beyond the scope of this paper; since the main aim is to present a new technique for generating miniaturized bandpass filter design based on a fractal iteration process. The dimensions of the perturbations of each filter must be tuned for 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 [18,19].

Slight tuning of the initially calculated value of L_o is necessary to be adjusted to the design frequency. Figs (2-3) show the layouts of the resulting dual-band bandpass filters and Table 1 summarizes their side lengths and the satisfied size reduction percentages as compared with the conventional square ring resonator. It is expected that the 3^{rd} and the 4^{th} iterations bandpass filter structures may satisfy further size reductions of about 72% and 78% respectively, if the fabrication tolerances permits to be implemented.

Table 1
Summary of the Dimensions, and the Size Reduction Satisfied of the Generated Filters.

Parameters \ Filter Type		Squ. Ring	1^{st} Iter.	2^{nd} Iter.
Side Length, mm	Calc.	13.50	10.45	8.10
	Sim.	13.07	10.24	8.00
Occupied Area, mm^2	Calc.	182.25	109.2	65.61
	Sim.	170.95	104.85	64.00
Size Reduction	Calc.	----	40.1%	64.0%
	Sim.	----	38.7%	62.6%

It is worth to mention that, the microstrip bandpass filter based on the 1^{st} iteration depicted in Fig (3), has a similar structure with that reported in [20]. In [20], the presented filter structure represents a technique to produce a size reduction of the conventional dual-mode square ring by modifying its shape. This technique has stopped at a single step and does not goes further; hence it can be regarded as just a single intermediate step in the more general technique presented in this paper.

The microstrip bandpass filter based on the 2nd iteration depicted in Fig (4) is similar in structure with that presented by [21]. Again, the presented filter structure can be considered as a single intermediate step in the fractal based technique presented in this paper, since it has neither based on predefined step nor it has any further extension.

4. Performance Evaluation

Filter structures, depicted in Figs.2 to 4, have been modeled and analyzed at an operating frequency, in the ISM band, of 2.4 GHz using the IE3D electromagnetic simulator from Zeland Software Inc. 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 to7 respectively.

Figs. 6 and 7, imply 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 deign 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 techniques used. Figs8 to 10 shows the current density patterns using the EM simulator for 2nd iteration dual-mode microstrip bandpass filter at 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 mode are excited as expected at all. In these figures, the same color code is used as an indication for the current densities.

The previous filter designs can easily be scaled to other frequencies required for other wireless communication systems. In this case, the resulting new filter will be of lager or smaller in size according to the frequency requirements of the specified applications.

5. Conclusions

In this paper, a novel fractal design scheme has been presented as a new technique for microstrip bandpass filter design based on dual-mode square ring resonator. Due to the space-filling property 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 40% and 64% 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 72% and 78% 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.

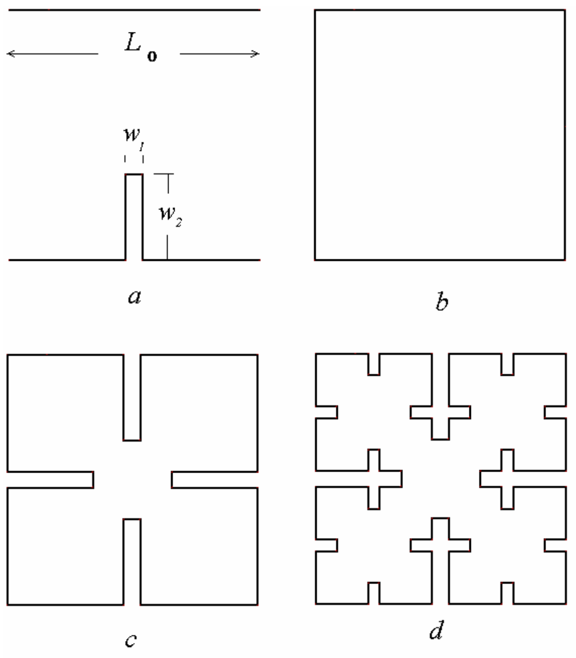

Fig. 1. The Generation Process of the Minkowski-like Prefractal Structure. (a) The Generator. (b) The Square Ring Resonator. (c) The 1st Iteration, and (d) The 2nd Iteration.

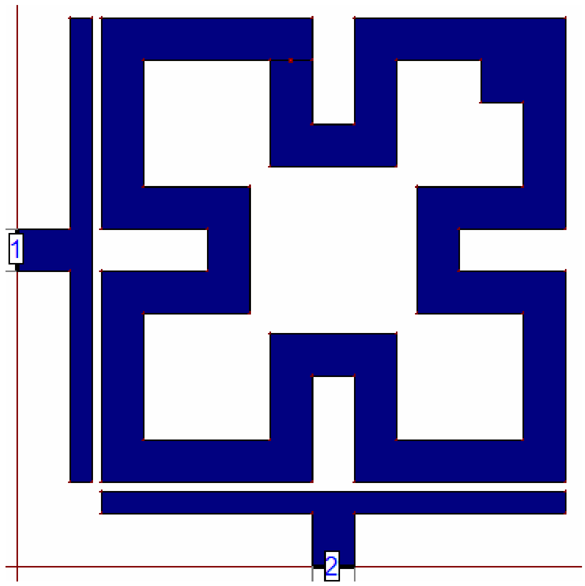

Fig. 3. The layout of the Dual-Mode Microstrip bandpass Fiber Base on the 1st Iteration.

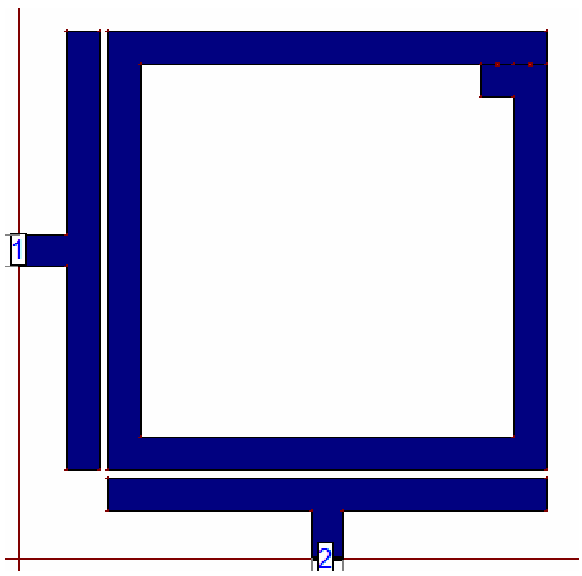

Fig. 2. The Layout of the Dual-Mode Square Ring Resonator, (The Intiation).

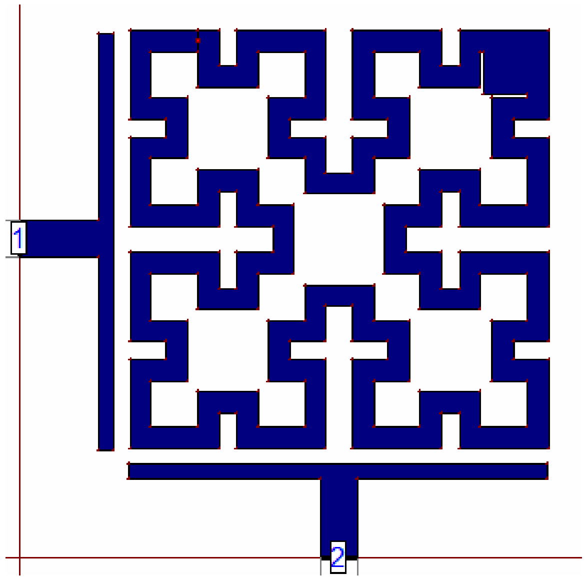

Fig. 4. The Layout of the Dual-Mode Microstrip Bandpass Filter Base on the 2nd Iteration.

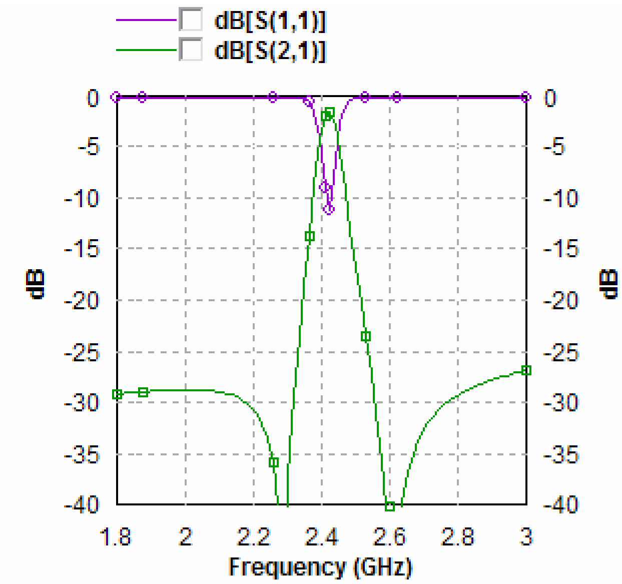

Fig. 5. The Return Loss and Transmission Responses of the Dual-Band Microstrip Square Ring Resonator.

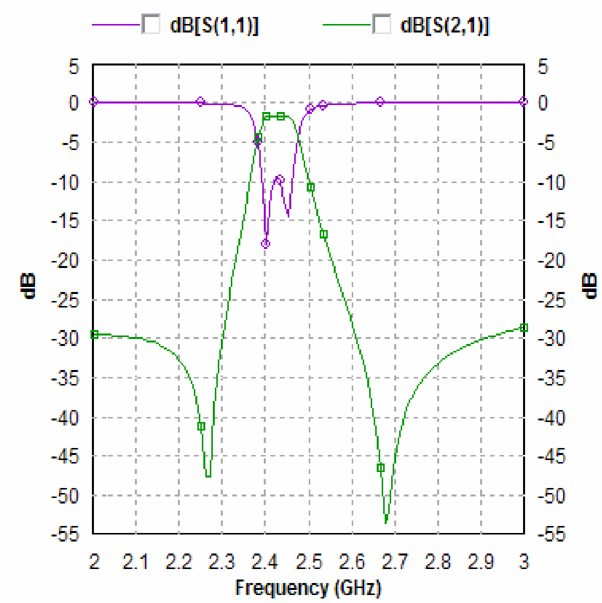

Fig. 7. The Return Loss and Transmision Response of the Dual-Band Microstrip 2nd Iteration Bandpass Filter.

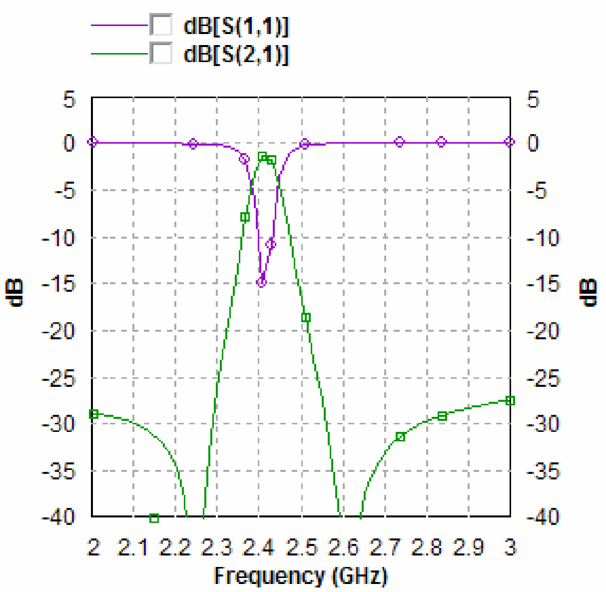

Fig. 6. The Return Loss and Transmission Response of the Dual-Band Microstrip 1st Iteration Bandpass Filter.

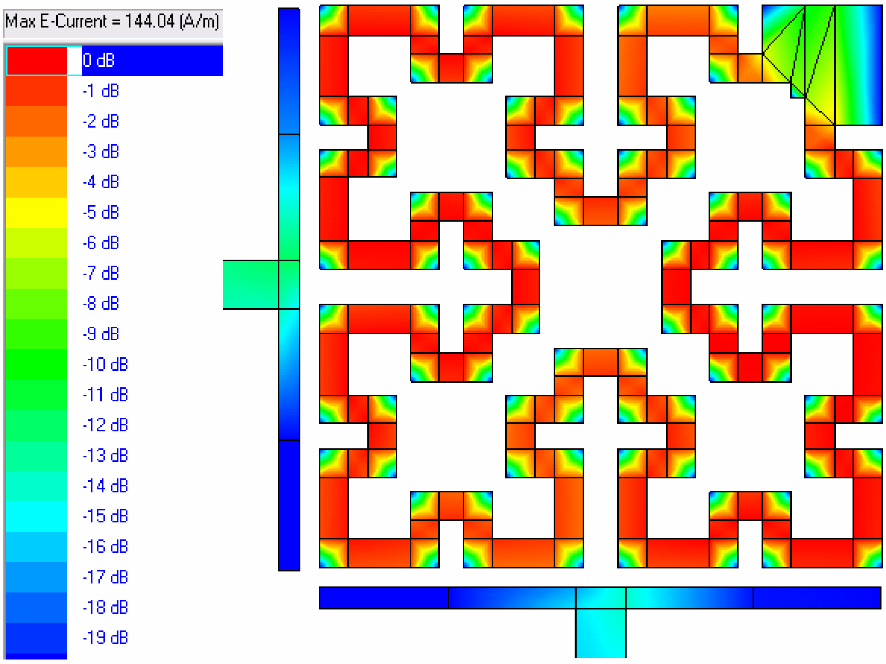

Fig. 8. Current Density Distribution at the Surface of the 2nd Iteration Microstrip Bandpass Filter Simulated at 2.4 GHz Resonance Frequency.

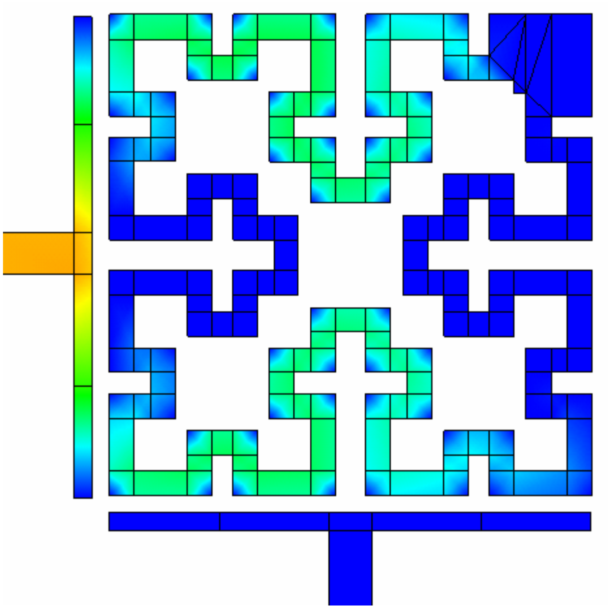

Fig. 9. Current Density Distribution at the Surface of the 2nd itEration Microstrip Bandpass Filter Simulated at a Frequency of 2.3 GHz.

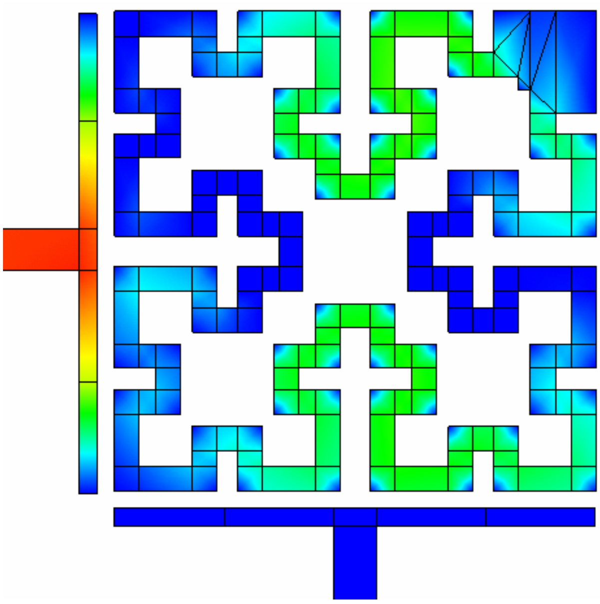

Fig. 10. Current Density Distribution at the Surface of the 2nd Iteration Microstrip Bandpass Filter Simulated at a Frequency of 2.5 GHz.

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تصميم مرشح امرار نطاقي ذي شريحة دقيقة متولد من الترتيب الهندسي الجزئي المبني على اساس المرنان الحلقي المربع ثنائي النمط لمنظومات الاتصالات اللاسلكية

جواد كاظم علي
قسم هندسة الكهرباء والالكترونيك/ الجامعة التكنولوجية

الخلاصة

يقدم في هذا البحث تقنية تصميمية مبتكرة مبنية على اساس الترتيب الهندسي الجزئي fractal geometry لتوليد سلسة تصاميم مصغرة القياس لمرشح الامرار النطاقي (BPF) ذي الشريحة الدقيقة تكون مناسبة لتطبيقات الاتصالات النقالة. ان التقنية التصميمية المقترحة مبنية على اساس مشابه لترتيب مينكويسكي الهندسي ما قبل الجزئي Minkowski-like prefractal geometry. ان خاصيتي املاء الفضاء والتماثل الذاتي اللتين يمتلكهما هذا الترتيب الهندسي تؤديان الى الحصول على تراكيب صغيرة الحجم ومتناظرة هندسيا في مستويات التوليد المختلفة، وتزداد هذه التراكيب صغرا بازدياد مستويات التوليد. ان تصاميم مرشحات الامرار النطاقي المبنية على اساس هذه التراكيب الهندسية تكون مصغرة وبأبعاد تجعلها مناسبة للاستخدام في انظمة الاتصالات الحديثة.

تم حساب اداء المرشحات الناتجة عن المستوين الاول والثاني باسخدام الحقيبة البرمجية IE3D التي تجري المحاكاة على وفق طريقة ايجاد العزوم (MoM)، وقد اظهرت النتائج ان المرشحين الناتجين لهما نسبتا تصغير قدرهما بحدود 40% و 64% مقارنة بأبعاد المرشح التقليدي المبني على اساس المرنان الحلقي المربع square ring resonator، شريطة ان تكون الظروف التصميمية نفسها في كلتا الحالتين. وعلاوة على ذلك ، فان التقنية التصميمية المقترحة ذات مرونة عالية حيث انها توفر لمصممي المرشحات (وغيرها من دوائر الموجات الدقيقة غير الفعالة) حرية اكبر في اختيار المعالم التصميمية، مقارنة بما تقدمه التصاميم المنشورة في الادبيات الهندسية للمرشح نفسه.