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A New Narrow Band Dual-Mode Miniaturized Bandpass Filter Design for Wireless Communication Systems

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Abstract

A new narrowband, compact, and low profile microstrip filter design is presented in this paper as a candidate for use in modern wireless systems. The proposed design is based on the use of fractal multiple ring resonator. Multiple ring resonators have advantages to possess much narrower and shaper performance responses than those of the single ring resonator. The proposed filter design is fractally generated using Minkowski-Like Pre-Fractal curve geometry applied to the conventional square microstrip square ring filter. Filter structures resulting from the successive iterations in the fractal generation process show a considerable size reduction compared with the conventional microstrip square ring filter designed at the same frequency using the same substrate material. The performance of the generated bandpass filter structures have been analyzed using method of moments (MoM) based software package Microwave Office 2007. Performance Simulation results show that filter structures employing 2nd and 3rd iterations offer size reduction percentages of about 61.5% and 77.7% respectively as compared with the conventional square ring filter.

Keywords: Dual-Mode ring resonator; narrowband filter; fractal filter; microwave bandpass filter

تصميم مرشح إمرار نطاقي ثنائي النمط مصغر و ضيق النطاق الترددي جديد لأنظمة الاتصالات اللاسلكية

الخلاصة

تم في هذا البحث تقديم تصميم مرشِح مصغر ضيق النطاق الترددي جديد لغرض استعمالِه في أنظمةِ الاتصالات اللاسلكية الحديثةِ. إنّ التصميمَ المُقتَرَحَ مستند على استعمال المرنانات الحلقيةِ المتعددة ذات الترتيب الهندسي الجزئي. تمتاز هذه المرنانات بأنها تمتلك انطقه ترددية أضيق ومنحنيات أداءِ حادة أكثر مِنْ تلك التي للمرنان ذي الحلقةِ الوحيدةِ. إنّ تصميمَ المرشِح المُقتَرَح قد جرى توليده باستعمال ترتيب مينكوسكي الهندسي ما قبل الجزئي المبني على أساس المرنان الحلقي المربع التقليدي. تمتلك المرشِحاتُ الناتجة مِنْ التكراراتِ المتعاقبةِ في عمليةِ توليد الترتيب الهندسي الجزئي تخفيضا كبيرا في الحجم ِ مقارنة بالمرشِح ذي الحلقةِ الواحدة التقليدي المصممَ في نفس الترددِ ويَستعملُ شريحة دقيقة بالمواصفاتِ نفسها. تم إجراء المحاكاة وحسابات الأداء النظري للمرشِحات الناتجةِ المناظرة لمستويات التوليد المختلفةِ باستخدام الحقيبة البرمجية(Microwave Office 2007).أظهرت نتائج تحليل أداء تركيبِ المرشِحين الناتجين عن التكرارين الثاني والثالثِ إنهما يمتلكان نسبتي تصغير قدرهما 61.5% و 77.7% مقارنة بالمرشِح الحلقي المربّع التقليديً.

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Introduction

Bandpass filter (BPF) is one of the most important components in microwave circuits. To meet the size requirement of modern microwave communications systems, compact microwave BPFs with narrowband is in high demand. Recently, there has been an increasing interest in planar BPFs due to their ease of fabrication. Filters using various planar resonators such as the open loop, miniaturized hairpin, stepped-impedance, quarter-wave, and quasi-quarter-wave resonators have been proposed for either performance improvement or size reduction.

Recent developments in wireless communication systems have imposed new challenges to design and produce high selectivity miniaturized components. These challenges stimulate microwave circuits designers and antennas designers to seek out for solutions by investigating different fractal geometries [1-5].

Fractal geometries are different from Euclidean geometries in that they 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 filter size. 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.

In this paper, a new four pole microstrip bandpass filter, based on double fractal dual-mode ring resonator, has been presented. filter structures are fractally generated based on Minkowski-like pre-fractal (MLPF) geometry, and using the conventional dual-mode square ring resonator as a starting step in the fractal generation process. The resulting filter structures are supposed to have miniaturized sizes with adequate reflection and transmission responses.

Minkowski-Like Pre-Fractal Geomet-ry for Miniaturized Filter Design

The starting pattern for the presented bandpass filter as a fractal is a square ring with a side length L_o, Figure (1.b). From this starting pattern, each of its four sides is replaced by what is called the generator structure shown in Figure (1.a). To demonstrate the fractal generation process, the first third iterations are shown. The first iteration of replacing a segment with the generator is shown in Fig(1.c). 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. In the traditional Minkowski island fractal, the generator is composed of five segments with equal length of one third. However in the present work, generator is composed of five unequal length segments. According to this, the term Minkowski-like pre-fractal has been used to describe the resulting pre-fractal geometry. The middle segment w_1 is chosen such that it is less 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 [6].

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 [7-11].

Practically, shape modification of the resulting structures in Fig(1.c, d, and e) is a way to increase the surface current path length compared with that of the conventional square ring resonator; resulting in a reduced resonant frequency or a reduced resonator size, if the design frequency is to be maintained. Theoretically the size reduction process goes on further as the iteration steps increase. It is expected then, that the 2nd iteration, shown in Fig(1.d) will exhibit further miniaturization ability owing to its extra space filling property.

The presented fractal scheme has an additional property that 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 [9, 10]. 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 [7-10]

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

where P_n is the perimeter of the nth iteration pre-fractal and a_2 is equal to 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 each iteration, was found very triggering for examining its size reduction capability as a microstrip bandpass filter. The length, L_o, of the conventional micro-strip dual-mode square ring resonator has been determined using the classical design equations reported in the literatures [12-15]. As shown in Figure (1), applying geometric transformation of the generating structure Fig.(1.a) on the square ring resonator Fig.(1.b), results in the 1st iteration filter structure depicted in Fig.(1.c). Similarly successive bandpass filter shapes, corresponding to the subsequent iterations can be produced as successive transformations have been applied. Fig.(1.e) shows an enlarged copy of the 3rd iteration fractal structure, on which the proposed bandpass filter design is based. At the n^{th} iteration, the corresponding filter side length L_n has been found to be [7-10]

$$L_n = (0.6)^{n/2} L_o \qquad .....(2)$$

while the enclosing area, A_n, has been found to be [7-10]

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

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

Two Pole Single Ring Filter Design

Up to 3rd iteration microstrip dual-mode single ring bandpass filter structures have been designed for the (ISM) band applications at a design frequency of 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 1.27mm. At first, the side length of the square ring resonator, L_o, has to be calculated as [12-15]

$$L_o = \frac{l_{go}}{4} \qquad .....(4)$$

where $l_{go} = c / f\sqrt{e_{eff}}$ is the guided wavelength and $e_{eff} = e_r + 1/2$.

Then the side length L_n for the successive iterations can be calculated, based on the value of L_o, using Equ.(2). Small perturbations have to be applied to each dual-mode resonator, at locations that are assumed at an angle 45^o offset from its two orthogonal modes. These perturbations are in the form of a small patch added to the square ring, and the other subsequent iterations 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 proposed resonating structures are characterized by their diagonal symmetry, this shape of perturbation is the most convenient to satisfy the required coupling [10,16]. 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 [17,18].

It is worth to mention that, the filter structures based on the 1st 2nd and 3rd iterations depicted in Figs.(3-5) have similar structures with those reported in [10]. These filter structures have been found to possess size reductions of about 40%, 64% and 78% respectively, as compared with those of the conventional dual-mode microstrip square ring resonator, Fig(2), with accepted filter performances [10]. Table (1) summarizes the resulting side lengths and the satisfied size reduction percentages against the conventional square ring resonator.

Four Pole Double Ring Dual-Mode Resonator Filter

Dual-Mode microstrip filters are composed of one or more dual-mode resonators [16]. Multiple ring resonator filters have advantages in acquiring a much narrower and shaper rejection band than the single ring resonator. The proposed four pole double ring filter structures, based on 2nd and 3rd iterations MLPF geometry, have been designed and simulated for the ISM band applications. In the realization of multiple ring filters based on dual-mode resonators, it is necessary to couple the modes of the different dual-mode resonator. In principle, this can be done simply by a distance which separates the two structures as sketched in Figs(6-9) for a four pole filters based on the fractal dual-mode ring resonators. In these figures, it has been also evidenced the presence of the four modes, by indicating the main directions of the corresponding current distributions.

Favoring the coupling between the modes 2 and 3 and reducing all the others, the coupling between the rings can be controlled either by the length *D* of the microstrip which connects the two stubs or by the capacitive gap *g* between the resonators and stubs. By using this layout, a four pole filter, with a center frequency of 2.4 GHz, has been designed on the same substrate that has been used for single resonator filter previously reported. The dimensions of the basic fractal dual-mode rings are unchanged as in the case of the corresponding single stage filters. The coupling between the degenerate modes of the rings is achieved by suitable perturbations. Table(2) summarizes the resulting dimensions and the satisfied size reduction percentages of the simulated four pole double ring filters against the conventional double square ring resonator filter. The values of *D* and the spacing *g* have to be tuned to achieve the required performance

Performance Evaluation

A Two pole dual-mode filter structure based on the conventional square ring resonator, and three filter structures corresponding to the first three fractal iterations, depicted in Figs(2-5) respectively, have been modeled and analyzed at an operating frequency, in the ISM band, of 2.4 GHz using the Microwave office 2007 electromagnetic simulator from AWR 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.(10 -13) respectively.

Results show that the resulting bandpass filters possess good performance curves. As can be seen, all of the filter responses show two transmission zeros symmetrically located around the deign frequency. 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 larger or smaller in size according to the frequency requirements of the specified applications.

Similarly, A four pole dual-mode filter structure based on the conventional square ring resonator, and three filter structures corresponding to the first three fractal iterations, depicted in Figs(6-9) respectively, have been modeled and analyzed at the same operating frequency. The correspond-ding simulation results of return loss and transmission responses of these filters are shown in Figs.(14-17) respectively. For demonstration, the surface current distribution of the 3rd iteration based double ring resonator filter has been shown in Fig.(18).

Conclusions

In this paper, a new miniaturized narrowband fractal four poles bandpass filter structures have been presented as a new technique for dual-mode narrow band BPF design. In this technique, the four poles dual-mode bandpass filter structures have been generated based on the 2^{nd} and 3^{rd} iterations Minkowski-like pre-fractal geometry and using the conventional dual-mode square ring resonator as an initiator. Up to the 3^{rd} iteration, double ring microstrip bandpass filters structures have been designed, according to this technique, and analyzed using the method of moments (MoM), at the ISM frequency band. Results showed that, these filters possess a progressive size reduction with reasonable return loss and transmission responses. The 2^{nd} and 3^{rd} iterations filters have been found to offer size reductions of about 61.5% and 77.7% respectively as compared with the conventional dual-mode microstrip square ring resonator under the same design specifications. Consequently, the proposed technique can be generalized as a flexible design tool for compact microstrip bandpass filters for a wide variety of wireless communication systems.

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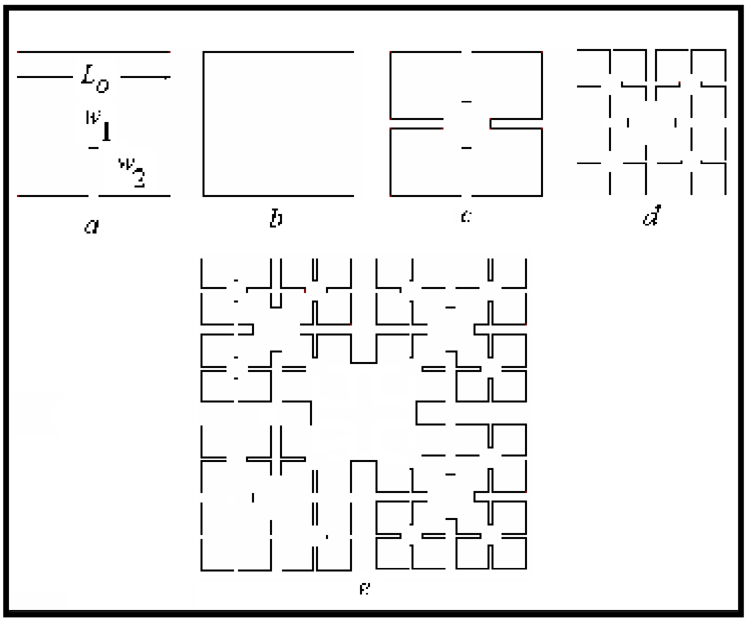
Table (1) Calculated and simulation results of the modeled dual-mode single resonator filters

Filter type / Parameter	Squ. Ring	1st Iter.	2nd Iter.	3rd Iter.
Side Length, mm	20.4	15.9	12.1	9.3
Occupied Area, mm^2	416.16	252.81	146.4	86.5
Size Reduction	-----	39.25%	64.82%	79.2%

Table (2) Calculated and simulation results of the modeled dual-mode double resonator filters

Filter / parameters	Zero- iter.	1st-iter.	2nd-iter.	3rd-iter.
Filter Dimensions, mm×mm	32×16.25	27×13.5	20×10	14.75×12.3
Occupied Area, mm^2	520	364.5	200	182.425
Size Reduction	-------	31.5%	61.5%	77.7%



Fig(1) The generation process of the Minkowski-like pre-fractal structure; (*a*) the generator, (*b*) the square ring resonator, (*c*) the 1st iteration, (*d*) the 2nd iteration, and (*e*) an enlarged copy of the 3rd iteration[10]

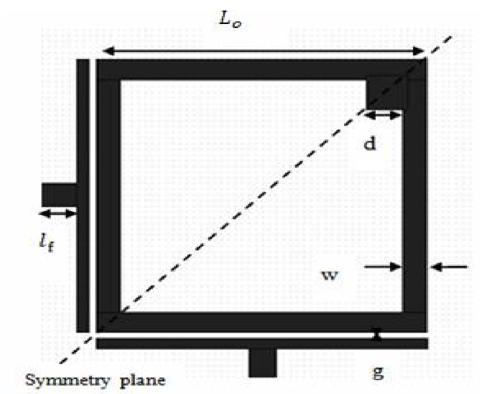


Fig.(2) The layout of the modeled dual- mode 2nd iteration MLPF microstrip resonator filter

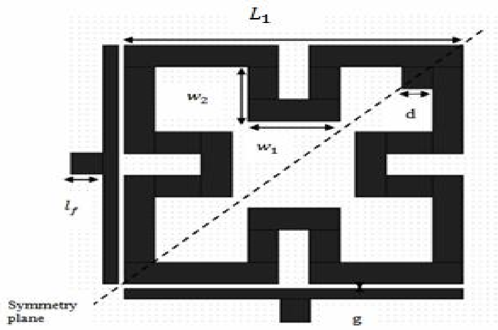


Figure (3) The layout of the modeled 1st iteration

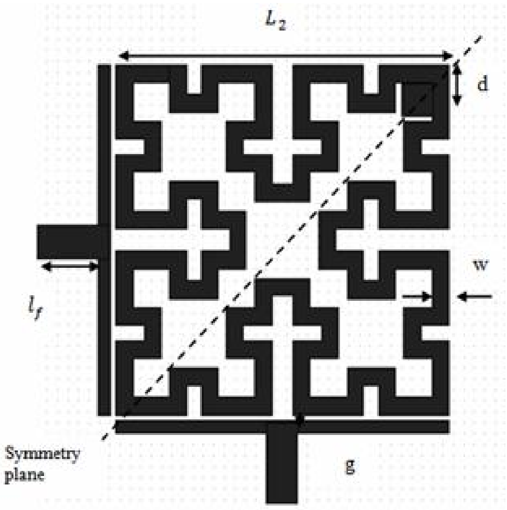
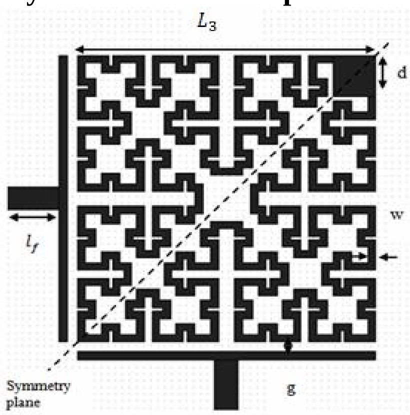


Figure (4) The layout of the microstrip resonator filter



Figure(5) The Layout of the modeled 3rd iteration MLPF microst1rip resonator filter

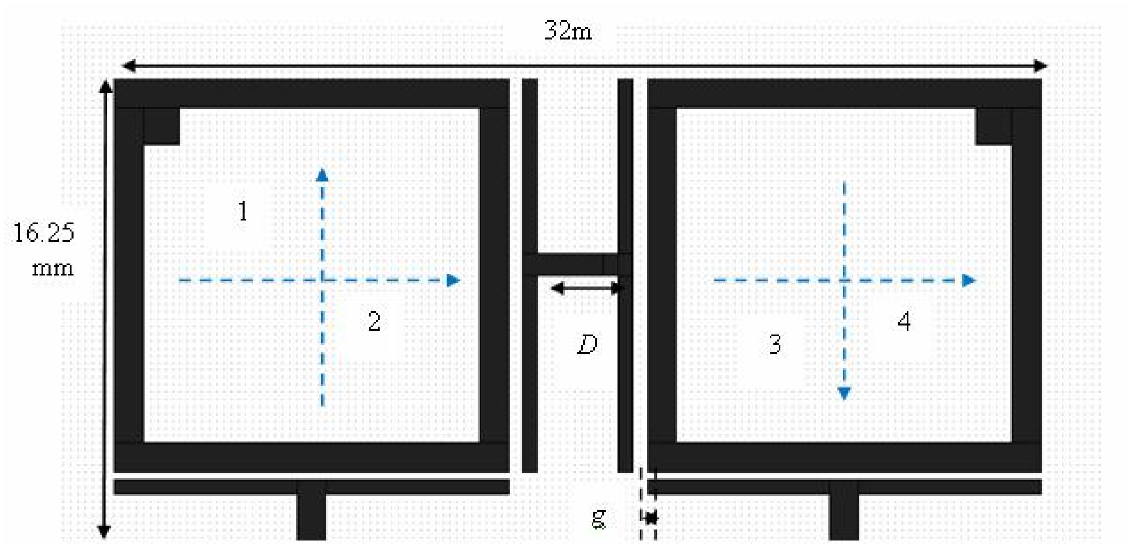


Figure (6) The layout of the modeled four pole conventional dual-mode square microstrip resonator filter designed for 2.4 GHz

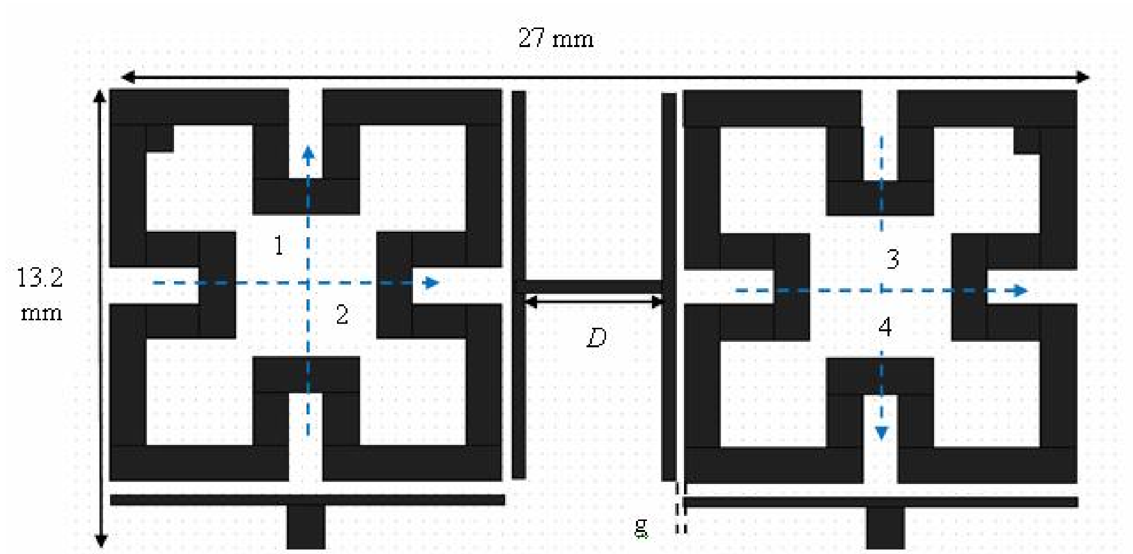


Figure (7) The layout of the modeled four pole 1st iteration MLPF microstrip resonator filter at a frequency of 2.4 GHz

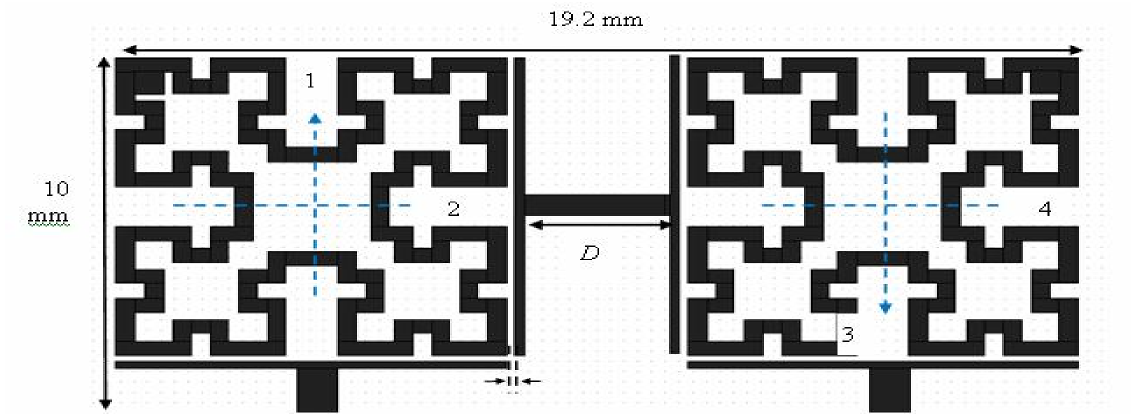


Figure (8) The layout of the modeled four pole 2nd iteration MLPF microstrip resonator filter at a frequency of 2.4 GHz

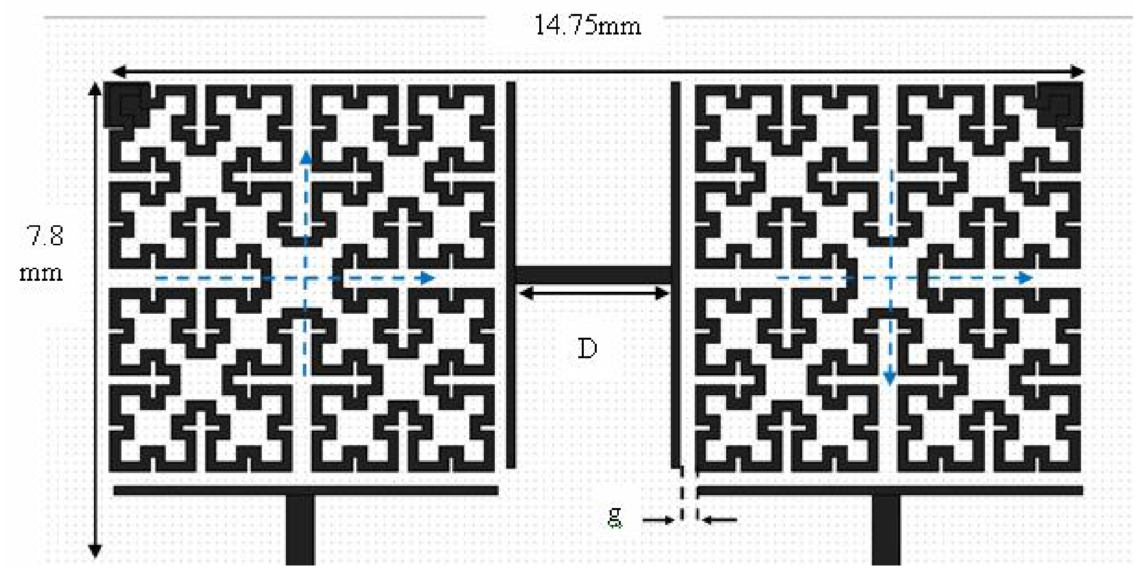
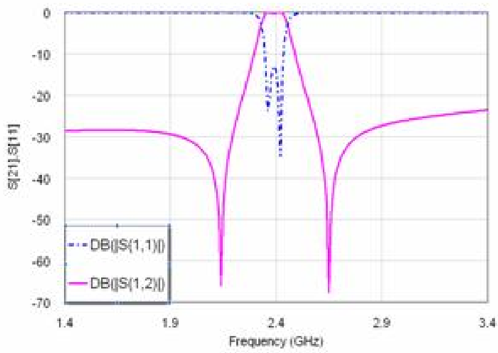
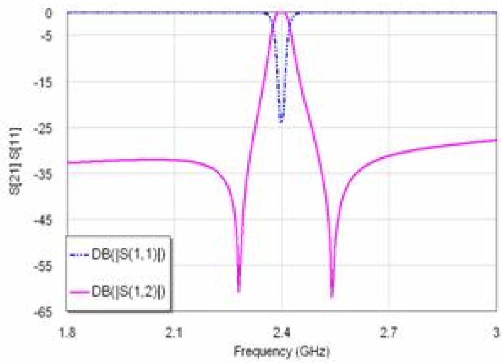


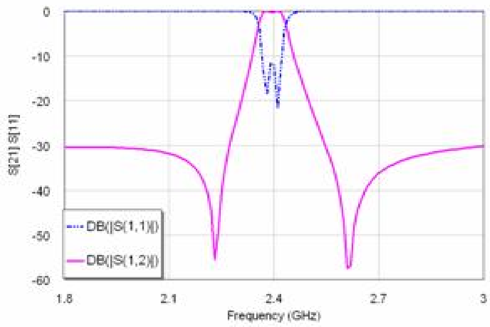
Figure (9) The layout of the modeled four pole 3rd iteration MLPF microstrip resonator filter at a frequency of 2.4 GHz



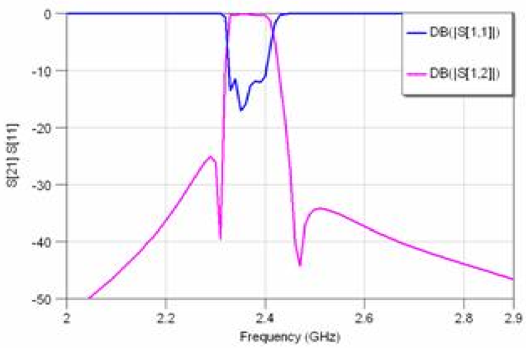
Fig(10) Return loss, S_{11}, and transmission, S_{21}, responses of a two pole conventional square ring microstrip resonator filter



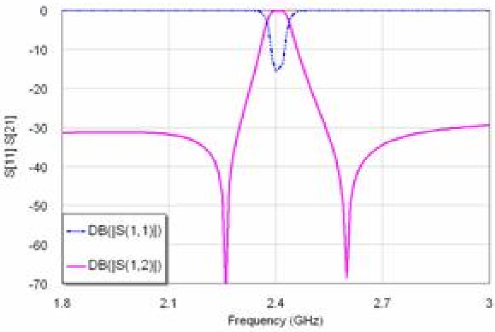
Fig(13) Return loss, S_{11}, and transmission, S_{21}, responses of the two pole 3rd iteration MLPF microstrip resonator filter



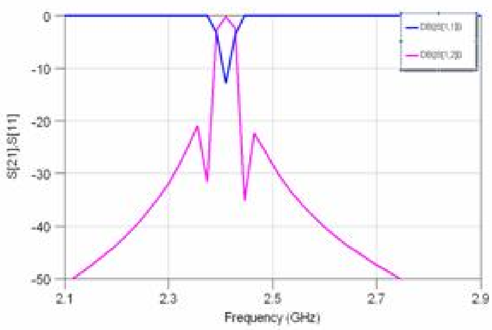
Fig(11) Return loss, S_{11}, and transmission, S_{21}, responses of a two pole 1st iteration MLPF microstrip resonator filter



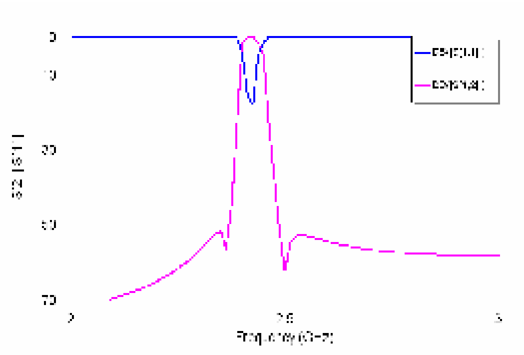
Fig(14) Return loss, S_{11}, and transmission, S_{21}, responses of four pole double square ring microstrip resonator filter



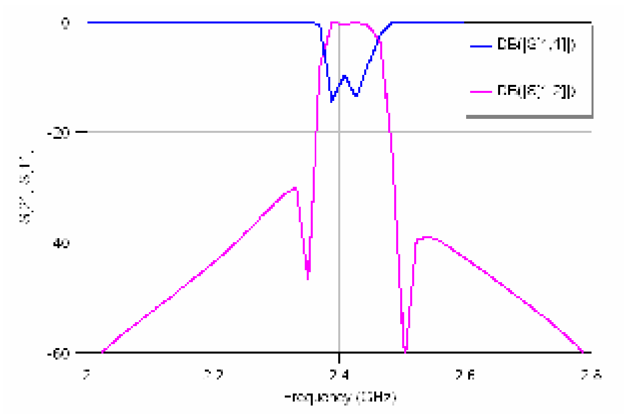
Fig(12) Return loss, S_{11}, and transmission, S_{21}, responses of the two pole 2nd iteration MLPF microstrip resonator filter



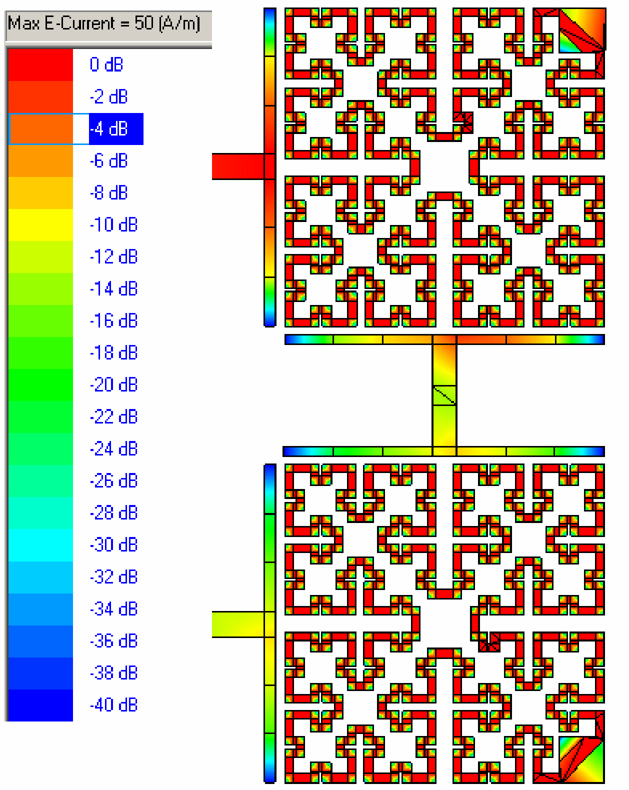
Fig(15) Return loss, S_{11}, and Transmission, S_{21}, responses of four pole 1st iteration MLPF microstrip resonator filter



Figure(16) Return loss, S_{11}, and transmission, S_{21}, responses of four pole 2^{nd} iteration MLPF microstrip resonator filter



Figure(17) Return loss, S_{11}, and transmission, S_{21}, responses of four pole 3^{rd} iteration MLPF microstrip resonator filter



Figure(18) Surface current distribution of the four pole microstrip bandpass filter based on the 3rd iteration fractal dual-mode ring resonator at the design frequency