Design of a New Reduced Size Dual-Mode Microstrip Resonator Bandpass Filter for Modern Wireless Applications

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Abstract

In this paper, the design of a new compact size dual-mode microstrip resonator is presented as a candidate for use in modern wireless applications. The proposed resonator structure is a result of applying two reduction techniques to the conventional square patch dual-mode microstrip resonator. First, the edges of the conventional square patch have been replaced by first iteration Koch pre-fractal curves. The proposed resonator filter has been designed for ISM band applications, at 2.4 GHz, using a substrate with a relative dielectric constant of 10.8 and thickness of 1.27 mm. This has shown to result in dual-mode resonator with a side length of 16.05 mm, which represents a size reduction of about 24%, as compared with the conventional square patch resonator using the same substrate and designed at the same frequency. Moreover, the resonator size has been further reduced by inserting a crossed slot in the patch structure. The resulting microstrip patch dual-mode resonator has been found to possess a side length of about 11.55 mm, which represents a size reduction of about 61% 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™ SSD electromagnetic simulator from Mentor Graphics Corporation. Simulation results show that the proposed filter has acceptable return loss and transmission responses besides the miniaturized size gained.

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

الخلاصة

تم في هذا البحث ، استعراض تصميم لمرشح امرار نطاقي جديد مصغر، مبني على اساس مرنان الرقعة المربع ثنائي النمط ذي الشريحة الدقيقة، للإستعمالِ في أنظمةِ الأتصالِ الحديثةَ ذات الاحجام المصغرة . جرى توليد شكل المرنان المُقتَرَحِ بإستعمال تقنيتي تصغير على المرنان المربع التقليدي ذي الشريحة الدقيقة ؛ وهما التكرار الاول للترتيب الهندسي الجزئي لمنحني كوخ بالاضافة الى الشقوق المتقاطعة في الشكل المربع للشريحة الدقيقة . أظهرت المرشحات ، التي تم تصميمها عند النطاق الترددي ISM ، بأنها تمتلك تخفيضا كبيرا بالحجمِ مقَارنةً بمرشح الرقعةِ المربع تقريبا التقليدي ، المصمّمَ عند الترددِ نفسه ويَستعملُ مواصفاتِ الشريحة الدقيقة نفسها. فقد اظهر المرشح المبني على اساس منحني كوخ لوحده تخفيضا بالحجم بقدر 24% تقريبا ، في حين اظهر المرشح المبني على اساس منحني كوخ بالاضافة الى الشقوق المتقاطعة تخفيضا بالحجم بقدر 61% تقريبا مقارنة بالمرشح ثنائي النمط المبني على اساس المرنان المربع ذي الشريحة الدقيقة التقليدي . نُفّذتْ المحاكاة وحسابات الأداء النظرية للمرشحات المقترحةِ بإستعمال حقيبة المحاكاة الكهرومغناطيسية المبنية على اساس طريقة ايجاد العزوم ،EI3 D ، ذات الإستعمالُ الواسع في البحثِ والصناعةِ في مجالهندسةالموجات الدقيقة. بينت نَتائِجُ المحاكاةِ لتصاميمِ المرشحات المُقترحة بأن لها استجابات ترددية جيدة لخسائر الفقد والانتشار بإلاضافةً إلى تمتعها بالحجم المصغر.

Introduction

Since the pioneer's work of Mandelbrot (1983), a wide variety of applications for fractal has been found in many areas of science and engineering. One such area is fractal electrodynamics (Jaggard, 1990) in which fractal geometry is combined with electromagnetic theory for the purpose of investigating a new class of radiation, propagation, and scattering problems. One of the most promising areas of fractal electrodynamics research is its application to the passive microwave circuit design. 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 (Kim et.al, 2006; Xiao et.al, 2007 and Wu et.al, 2008).

Two common properties; space-filling and self-similarity, fractal geometries have, 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 (Ali, 2008a; Ali and Hussain, 2009). Space-filling property of many fractals can be utilized to realize reduced size single-mode microstrip bandpass filters (Barra et.al, 2005; Ali and Miz'el, 2009). 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 (Ali, 2008a). Among the earliest predictions of the use of fractals in the design and fabrication of filters is that of (Yordanov et.al, 1991). Their predictions are based on their investigation of Cantor fractal geometry.

In this paper, new miniaturized design structures for the dual-mode microstrip bandpass filters, based on applying Koch pre-fractal curve to the conventional microstrip dual-mode square patch resonator and crossed slot patterns inside the patch itself. The resulting dual-mode 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.

The Filter Structure Generation Process

The first miniaturization technique of the proposed dual-mode microstrip patch resonator is to apply Koch fractal curve geometry. 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 (Falconer, 2003). 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 (Ali and Hussain, 2009):

$$P_n = \left(\frac{4}{3}\right)^n P_{n-1} \qquad (1)$$

where P_n is the perimeter of the nth 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 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 (Ali, 2008b).

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; resulting in a reduced resonant frequency or a reduced resonator size, if the design frequency is to 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 (Chang and Hsieh, 2004; Hong and Lancaster, 2001).

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 (Chang and Hsieh, 2004; Hong and Lancaster, 2001) 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 miniaturization step has been supposed to be completed. The second step, according to the proposed technique, is to implement a crossed slot pattern inside the Koch fractal based microstrip patch resonator structure resulting from the previous step.

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 two bandpass filters with their microstrip patch resonators are in the form of the conventional square and the first iteration Koch fractal curve. The second set of filters is the same as those described in the first set, but with crossed slot structures implemented in their 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 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 transmission lines.

At first, the side length of the square ring resonator, L_o, has to be calculated as (Chang and Hsieh, 2004; Hong and Lancaster, 2001).

$$L_o \leq \frac{\lambda_g}{2} \qquad (2)$$

where λ_g is the guided wavelength, given by (Edwards, 1981):

$$\lambda_g = \frac{\lambda_\circ}{\sqrt{\varepsilon_{re}}} \qquad (3)$$

where $\lambda_\circ$ is operating wavelength at the design frequency, and ε_{re} is the effective dielectric constant given by (Edwards, 1981):

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{w}\right)^{-0.5} \qquad (4)$$

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 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 should not be discussed this paper; 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 (Görür, 2004; Amari, 2004).

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 be implemented 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 slot length will stand for the required perturbation. Figure 2 shows the layouts of the resulting dual-band microstrip patch bandpass filters.

The resonating side length of the square patch resonator, Fig. 1a, 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, Fig. b, 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, Fig, 1d, is of about 11.55 mm with slot length and width of 12.9 mm and 0.35 mm respectively. The crossed slot structures, introduced in the patch resonators depicted in Figs. 1b and 1d, have a considerable impact in size reduction of these resonators as compared with those depicted in Figs. 1b and 1d.

Table (1) summarizes the resulting side lengths and the satisfied 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.

Filter Performance Evaluation and Simulation Results

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 IE3D SSD electromagnetic simulator from Mentor Graphics Corporation (IE3D, 2011). 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. 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.

Figure (7) illustrates the current density patterns using the EM simulator for the dual-mode microstrip bandpass filter, based on the first iteration Koch fractal curve patch resonator depicted in Fig. 2d, 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 modes are excited as expected at all. In these figures, the same color code is used as an indication for the current densities. It is clear that maximum current densities occur at the resonant frequency, as Fig. 7b implies.

The prescribed 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.

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 on the conventional square patch microstrip resonator.

Microstrip dual-mode bandpass filters based on the first iteration Koch fractal curve, with and without crossed slot structure, have been designed and analyzed using the method of moments (MoM) at the ISM frequency 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%. Simulation results show that these filters possess reasonable return loss and transmission performance responses. As the practical fabrication tolerances may permit, it is expected that filter structures based on higher iterations will offer further size reductions 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.

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TABLE I

Summary of the dimensions and the size reduction percentages of the modeled dual-mode patch bandpass filters

Filter Type		Side Length (mm)	Size Reduction %
Square patch (zero iteration)	Without slot	18.40	-----
	With slot	12.15	57
1st iteration	Without slot	16.05	24
	With slot	11.55	61

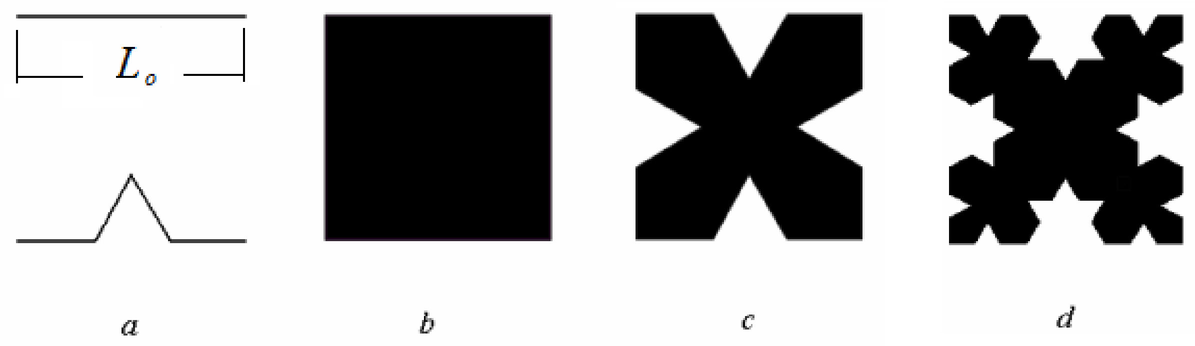

Fig.1 The generation process of the proposed fractal microstrip patch antenna structures based on fractal Koch curve. (a) the generator. (b) the initiator (square patch antenna), (c) the first iteration, and (d) the second iteration.

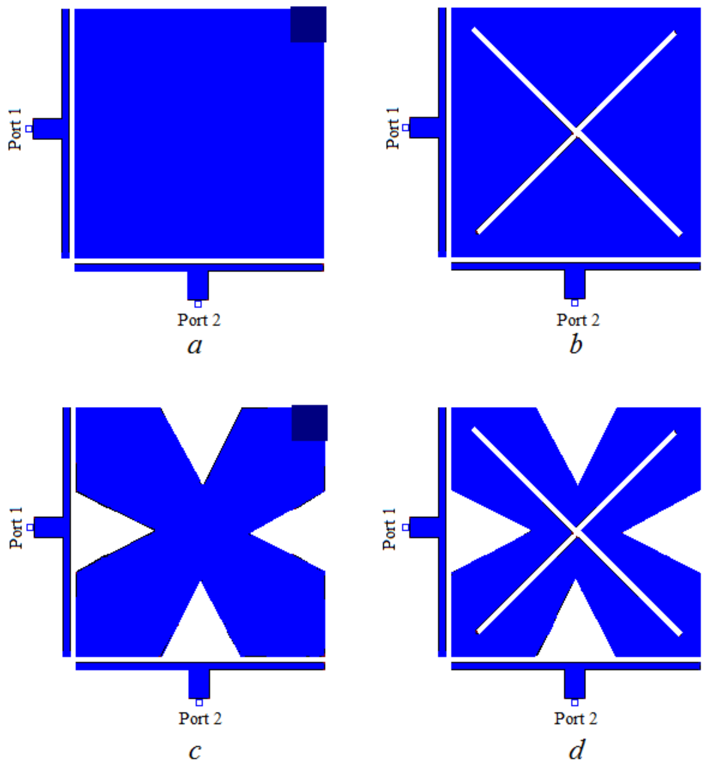

Fig.2 The layouts of the modeled dual-mode microstrip patch bandpass filters with resonators based on (a) the conventional square patch, (b) the conventional square patch and a crossed slot structure, (c) the first iteration fractal Koch curve patch, and (d) the first iteration fractal Koch patch curve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

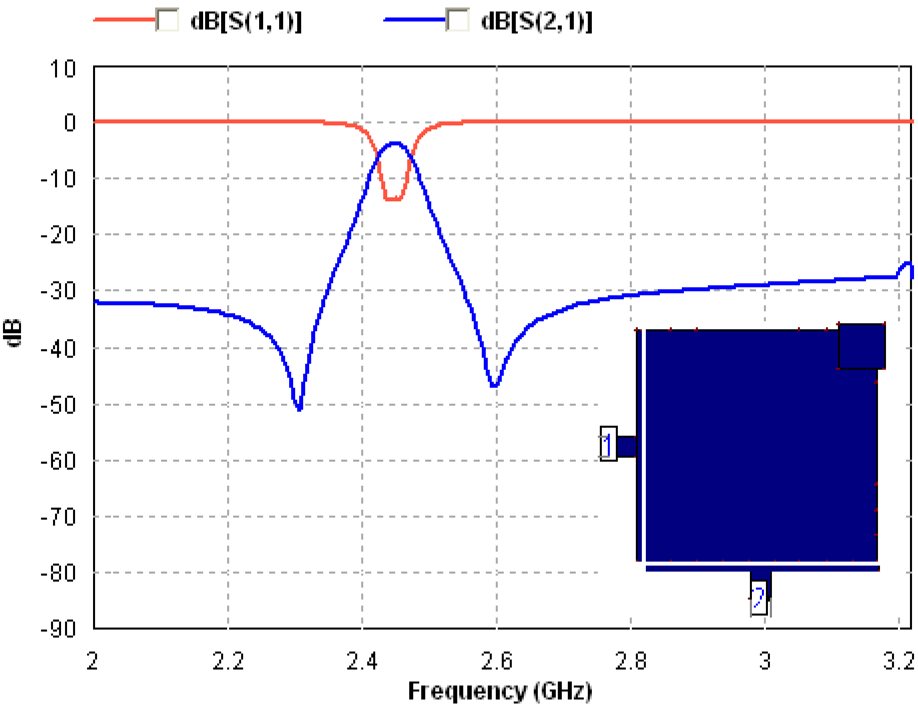

fig3.the return loss and transmission responses of the dual-mode microstrip square patch resonator depicted in Fig.2a.

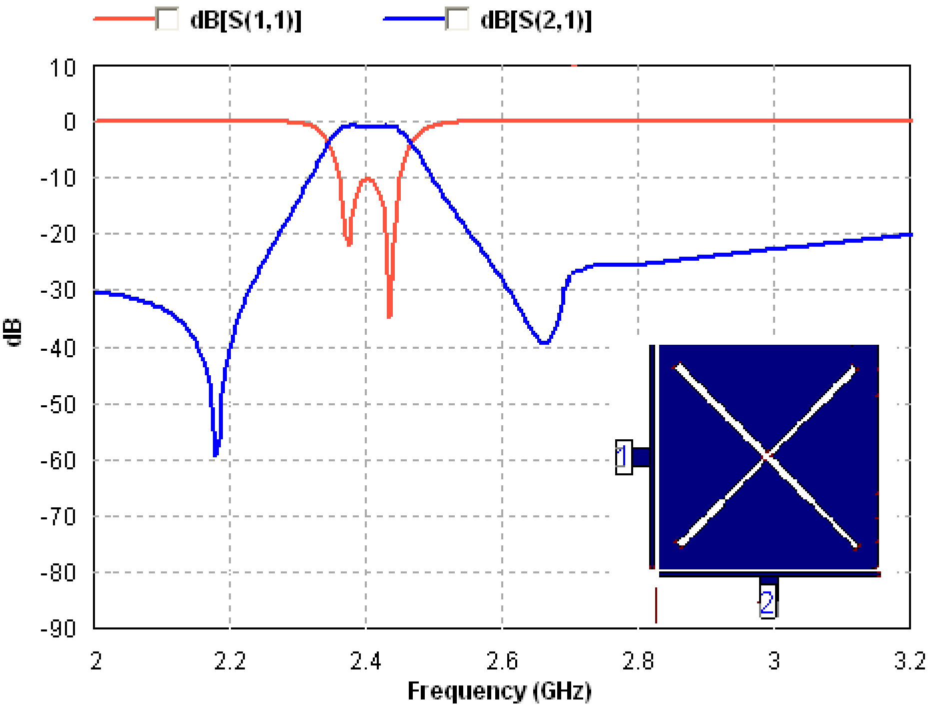

Fig.4. The return loss and transmission responses of the dual-mode microstrip square patch resonator depicted in Fig. 2b.

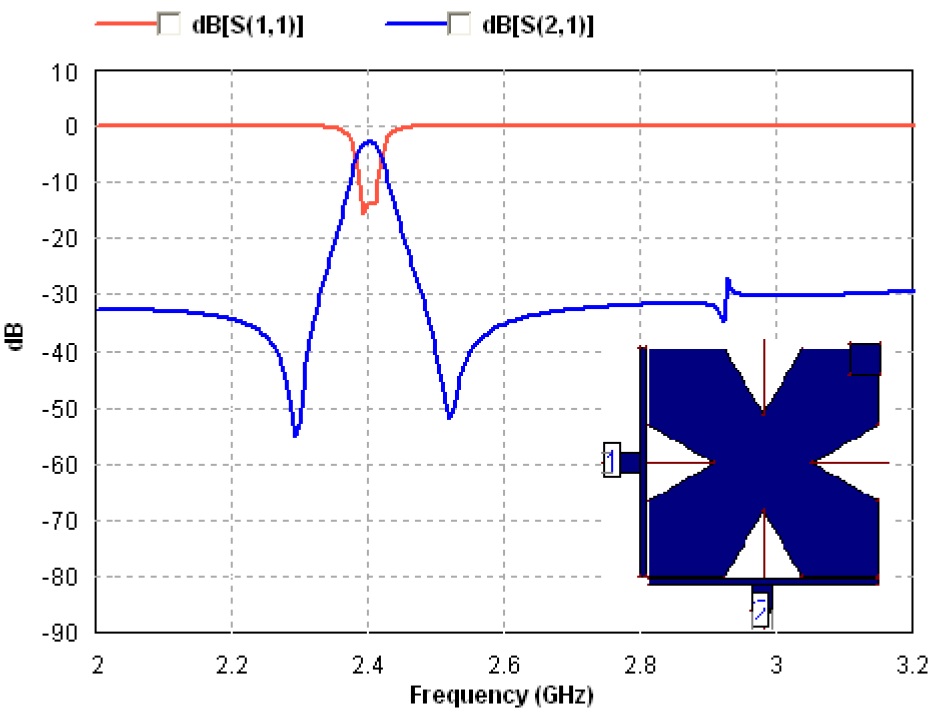

Fig.5. The return loss and transmission responses of the dual-mode microstrip square patch resonator depicted in Fig. 2c.

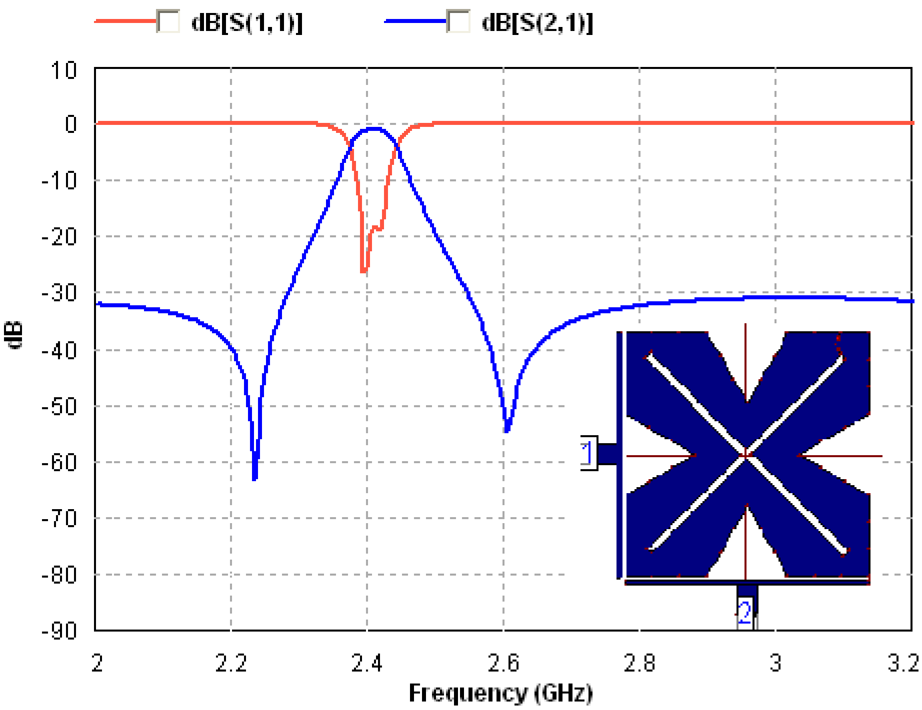

Fig.6. The return loss and transmission responses of the dual-mode microstrip square patch resonator depicted in Fig. 2d.

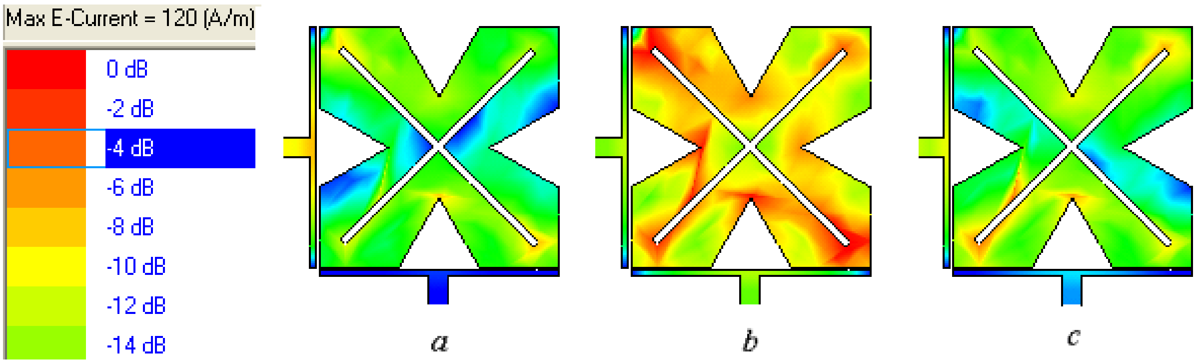

Fig. 7. Current density distribution at the surface of the first iteration microstrip bandpass filter with slots simulated at frequency of (a) 2.3 GHz, (b) 2.4 GHz, and (c) 2.5 GHz.