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DESIGN OF TRIPLE-MODE BANDPASS FILTER USING IMPROVED HEXAGONAL LOOP RESONATOR

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Abstract—A novel triple-mode hexagonal bandpass filter with capacitive loading stubs is introduced in this article. The technique, adding an open capacitive stub, is applied to enlarge the equivalent self-capacitance of the resonator, which declines its resonant frequencies. Three radial-line stubs in the center of top layer are used to implement this technique. One mode resonant frequency is varied with the radii of three radial-line stubs, while the other two modes are nearly not affected. This filter has a pair of transmission zeros which are close to the passband, thus it behaves with high selectivity. For method validation, a bandpass filter operating at 2.4 GHz is fabricated and measured. The experimental results are demonstrated and discussed.

1. INTRODUCTION

With the rapid development of modern mobile and wireless communication systems, the need for filters is challenged by not only its compact size but also the high performance. To make the filters more compact, one of the effective ways is to modify the traditional resonator to generate additional modes, causing the resonator to have multiple resonant frequencies, thus one resonator in physical can be treated as multiple resonators in electrical [1]. Among them, dual-mode filter is the most common multiple-mode filter, which has been analyzed deeply and comprehensively in many literatures with various configurations [2–8]. However, triple-mode or other multimode microstrip planar filters are rarely reported in literatures. Recently, Xue et al. [9] proposed a compact microstrip resonant cell (CMRC) structure, which is essentially a triple-mode resonator. A novel multimode bandpass filter with good rejection

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band is proposed by using a radial-line stub in [10]. A modified circular resonator with etched slots was employed to design triple-mode filter [11]. Also, a quadruple-mode planar bandpass filter with improved out-of-band rejection was realized in ultra-wideband (UWB) frequency response [12].

In this paper, we will present a different type of triple-mode filter by using a novel improved hexagonal multiple-mode resonator. The hexagonal multiple-mode resonator is developed from a conventional hexagonal loop dual-mode resonator. By introducing three radial-line stubs in the center of the top layer, one mode resonant frequency declines fast, while the other two modes are hardly changed, and with a pair of nonorthogonal input/output feeding lines, a triple-mode planar bandpass filter is realized. This filter with a pair of transmission zeros close to the passband shows a high selectivity. At last, the triple-mode filter is fabricated and measured. Both the simulated and measured results are presented.

2. TRIPLE-MODE RESONATOR DESIGN

Typical hexagonal loop dual-mode resonator is shown in Figure 1(a). It was deeply analyzed in [13]. For a loop resonator, it will resonate at its fundamental frequency when its median circumference is equal to the guided wavelength at the fundamental resonant frequency, and the higher resonant modes occur at any multiple of the fundamental resonant frequency. Figure 1(b) shows a modified hexagonal loop resonator. The center of the hexagonal loop resonator is connected by three microstrip lines with three alternate vertexes of the loop resonator respectively. In contrast to the resonator Type-I, a third mode is introduced between the fundamental modes and high-order modes. Figure 1(c) shows the configuration of the proposed triple-mode filter using another modified hexagonal loop resonator with all the geometrical dimensions. Three radial-line stubs with the same radius r_2 are connected to the center of the resonator towards the rest three vertexes of the resonator type-II.

Radial-line stub has been deeply researched in [14, 15]. It exhibits very low characteristic impedance in a wide band and has a smaller area contrasted to the traditional low impedance microstrip line with equivalent characteristic impedance. Thus, it has been applied to filters [16, 17] and various microwave circuits. In our design, it has been used as a capacitive loading to decrease the frequency of third mode. Meanwhile, it would not introduce other needless modes while other capacitive loading structures would, such as stepped impedance microstrip line.

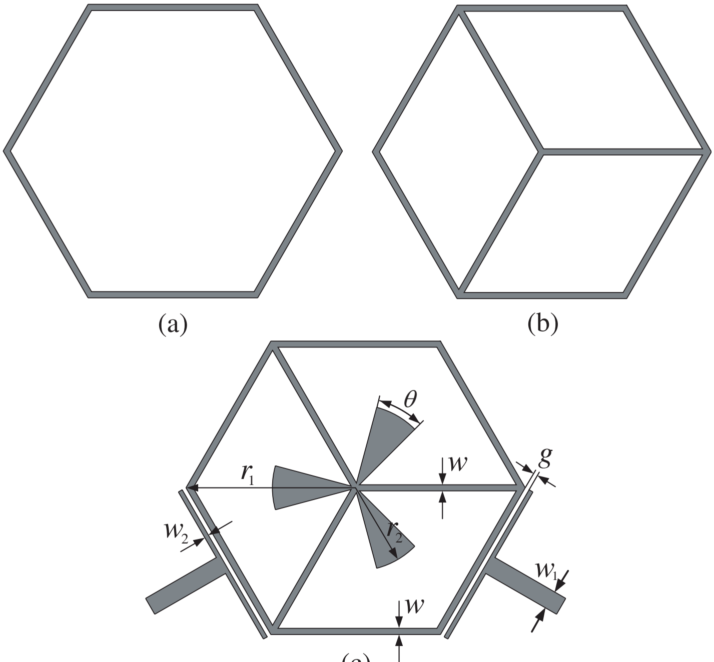

Figure 1. (a) Typical hexagonal loop resonator, Type-I, (b) modified hexagonal loop resonator, Type-II, (c) configuration of the proposed triple-mode filter using another modified resonator Type-III.

The three resonators with same geometrical dimensions have been simulated by a commercially full-wave electromagnetic (EM) eigenmode simulator. The Rogers TMM10 thermoset polymer composites with 1 mm thickness and relative dielectric constant of 9.2 is used as substrate, and all the parameters are as follows: $r_1 = 9.7$ mm, $r_2 = 4.75$ mm, $w = 0.3$ mm, and $\theta = 30$ deg. The first five resonant frequencies of the three resonators are listed in Table 1. For resonator Type-I, Mode-I and Mode-II are two degenerate modes. When no perturbation is introduced, their resonant frequencies are the same. Mode-III and Mode-IV are also two degenerate modes, and their resonant frequencies are nearly two times of Mode-I and Mode-II. For resonator Type-II, a third mode herein named Mode-III is generated, and the resonant frequency lies between the first two modes and the high-order modes. The first two modes resonant frequencies are slightly greater than that of resonator Type-I. When it comes to resonator Type-III, it is interesting to notice that the third mode resonant

Table 1. First five resonant frequencies of three resonators (GHz).

	Type-I	Type-II	Type-III
Mode-I	2.195	2.469	2.474
Mode-II	2.201	2.473	2.476
Mode-III	4.348	3.571	2.352
Mode-IV	4.357	4.244	4.224
Mode-V	6.390	4.252	4.227

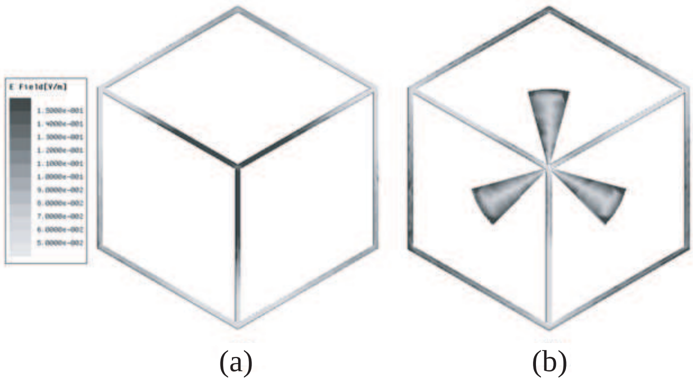

Figure 2. Electric field magnitude of the third mode. (a) Resonator Type-II, at 3.571 GHz, phase = 0 deg, (b) resonator Type-III, at 2.352 GHz, phase = 0 deg.

frequency declines from 3.571 GHz in resonator Type-II to 2.352 GHz in resonator Type-III for the effects of capacitive loading, while the other resonant frequencies are almost not affected.

Figures 2(a) and (b) depict the simulated electric field magnitude of the third mode in a transverse cut of substrate before and after with three radial-line stubs. As seen from Figure 2(a), the resonator Type-II with no radial-line stubs has a third mode resonating at 3.571 GHz, and its maximum electric field distributes in the center of the resonator. Figure 2(b) shows the electric field distribution of proposed resonator Type-III. The capacitive loading technique is implemented, which makes the resonant frequency of the third mode decline fast. The maximum electric field distributes around the brink of radial-line stubs instead of the resonator center.

At the same time, it is found that only the third mode of the first five resonant modes have a maximum electric field at the resonator center for resonator Type-II. Developed from resonator Type-II, it can be studied that only one mode resonant frequency of resonator Type-III is changed with the radii of radial-line stubs. Figure 3 depicts the simulated resonant frequencies of the first five modes as a function of the radii r_2 of radial-line stubs. Mode-I and Mode-II have nearly the same resonant frequencies, and their resonant frequencies are hardly changed. For Mode-III, its resonant frequency is shifted down fast from 2.721 GHz to 2.279 GHz as the radii of radial-line stubs are increased from 3.3 mm to 5.1 mm. But for Mode-IV and Mode-V, their resonant frequencies decline about 100 MHz. It can be concluded that the first three resonant modes of the resonator Type-III can be obtained separately to meet our demands by adjusting the radii of hexagonal loop and radial-line stubs. So, the design of triple-mode filter using this kind of resonator is flexible and very fast.

3. TRIPLE-MODE FILTER DESIGN AND EXPERIMENT

As can be seen from Figure 1, the resonator Type-II and Type-III have three-fold rotational symmetry. This means that if rotating the whole structure by 120 degrees with center of the resonator, then it is moved onto itself. Meanwhile, from Figure 2, it is found that electric field

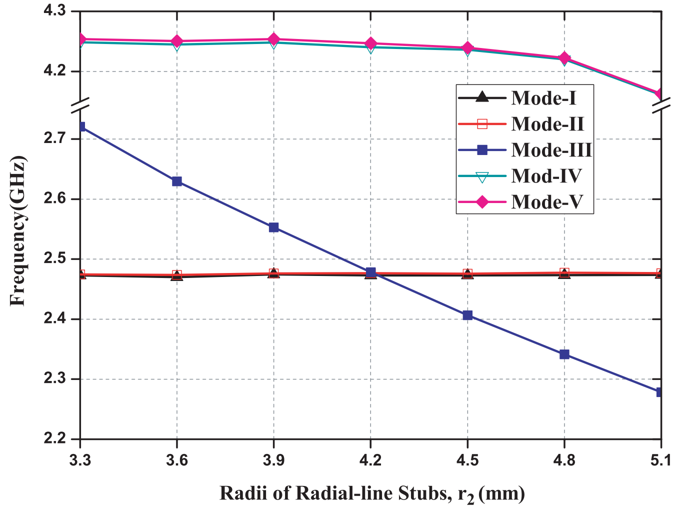

Figure 3. Simulated resonant frequencies of the first five modes as a function of the radii of radial-line stubs.

distribution of the third mode also has three-fold rotational symmetry. For coupling with the first three modes directly, a pair of nonorthogonal input/output feeding lines is coupled to two alternate sides of the hexagonal loop closely. The whole structure of triple-mode filter is shown in Figure 1(c). Some geometry parameters adopted are as follows: $r_1 = 9.7\,\mathrm{mm}$, $r_2 = 4.75\,\mathrm{mm}$, $w = 0.3\,\mathrm{mm}$, $\theta = 30\,\mathrm{deg}$, $g = 0.2\,\mathrm{mm}$, $w_1 = 1\,\mathrm{mm}$, and $w_2 = 0.2\,\mathrm{mm}$. The filters using resonator Type-I and Type-II with the same input/output ports are also simulated, and their frequency responses are depicted in the same coordinates with that of the triple-mode filter in Figure 4. It can be clearly seen that only the proposed triple-mode filter has a pair of transmission zeros. The minimum insertion loss is about 1.4 dB, and the return loss is greater than 17 dB in passband. At the same time, the locations of passbands validate the modes distribution as described in Section 2 for the three filters with the same dimensions.

Depending on the discussions above, a triple-mode bandpass filter is fabricated. Figure 5 shows the photographs of the fabricated triple-mode filter. The simulated and experimental frequency responses of the proposed triple-mode filter are shown in Figure 6. The simulated results show that the triple-mode filter operated at 2.4 GHz has a fractional bandwidth of 4.79%. A pair of transmission zeros are located at 2.263 GHz and 2.495 GHz respectively, which provide a better cutoff rate in the stopband and improve the selectivity. It is interesting to

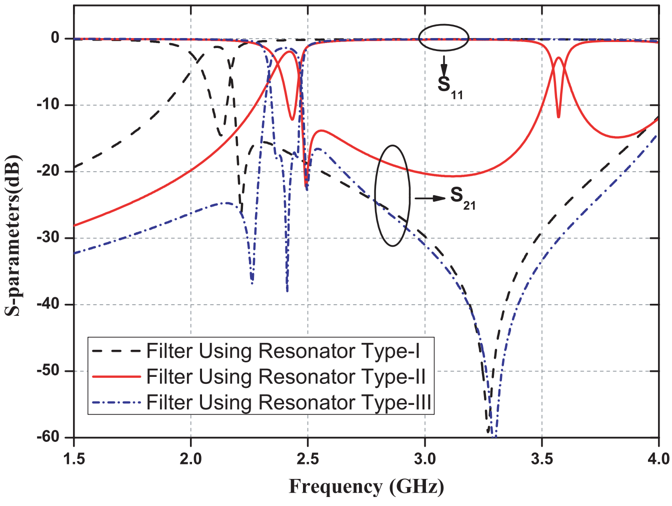

Figure 4. Simulated frequency responses of filters using resonator Type-I, Type-II, and Type-III.

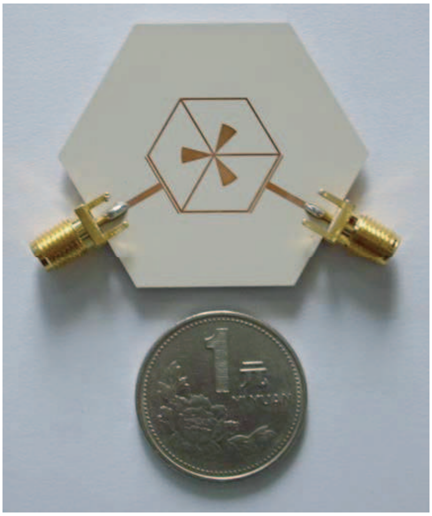

Figure 5. Photographs of the fabricated triple-mode filter.

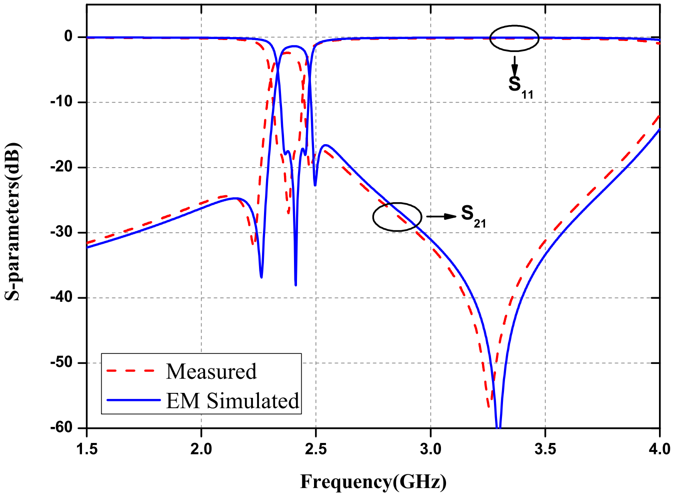

Figure 6. Simulated and measured frequency responses of the triple-mode filter.

notice that there is an additional transmission zero at 3.295 GHz which is mainly caused by the high-order modes and should be useful for the rejection of the interference in the passband. The measured results are slightly shifted up about 30 MHz in contrast to the simulated results. The measured minimum insertion loss is about 2.4 dB in the passband, which is mainly due to the conductor and dielectric losses of the substrate. Both the simulated and measured results are in good agreement.

4. CONCLUSION

A novel improved hexagonal loop resonator has been designed, discussed in this article. In Contrast to the typical hexagonal loop resonator, the proposed improved resonator can support three fundamental modes, and three modes resonant frequencies can be easily adjusted while the others are nearly not affected. It provides a convenient method to design a triple-mode filter using this novel improved hexagonal resonator with a pair of transmission zeros close to the passband. A triple-mode bandpass filter based on the proposed resonator with a center frequency at 2.4 GHz has been fabricated and measured. Both the simulated and measured results are presented and discussed. The superior features of designing this kind of filters indicate that it has the potential to be utilized in microwave planar circuits.

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