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TRIANGULAR RESONATOR BANDPASS FILTER WITH TUNABLE OPERATION

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Abstract—Triangular patch resonator bandpass filters with tunable operation are developed to perform nicer filter properties of low passband insertion loss, transmission zeros and wide stopband. With tunable fractal-shaped defection acts as perturbation, filter operation frequency and operation band can be controlled, and the responses of undesired resonant modes are greatly weakened even suppressed. The new design can bring filters more operation without changing the dielectric substrate or patch size. The designed filters have outstanding advantages of single patch with compact size and without resonator coupling gaps, simple circuit topology, nicer performances, miniaturization and can be easily tuned for more applications. All these features are well popular for wireless communication systems.

1. INTRODUCTION

Microstrip filters have been widely used in a variety of RF/microwave circuits and systems for their attractive features of low cost, easy fabrication, small sizes and so on. Currently, patch resonators are well popular in planar filters application, for they have more compact sizes, simpler structures reducing the design complexity and fabrication uncertainty, lower loss, higher power handling features and easier miniaturization etc. compared with the line-based resonator filters [1, 2]. With the rapid development of modern communication systems, more and more miniature planar filters [3–7] with excellent performances are required. Microstrip triangular resonator has important application in microwave circuits, especially the equilateral one, which is studied by Helszajn and James [8] firstly, later, Hong et al. [9, 10] implement some filters using this kind of resonator. However, the reported works [9–12] based on triangular resonators are limited compared with that of square and circular ones, and most of the reported filters consist of several resonators and exist of coupling gaps, which bring larger sizes. Literature [12] gives a dual-mode bandpass filter using triangular loop resonator, however, it only operates at a single band and single frequency, and only one transmission zero is implemented.

The basic principle for designing a patch resonator filter is the selectivity and application of all sorts of resonant modes. Currently, many patch filters are designed with dual-mode (the dominant mode and its degenerate mode) operation, and the numerous higher order modes are not applied. In our design, higher order modes are utilized and filter operations are extended. For the filter first higher order mode operation, the responses of neighboring modes such as the dominant mode ought to be weakened even suppressed, and simultaneously its resonance should be as far as possible from the operating frequency in order to minimize the interference, and it's the same for the other modes operation. The most feasible way for this implementation is a proper perturbation. In this article, patch etched defection which may be called fractal [13, 14] defection is introduced to act as the perturbation, and if it is properly controlled, operation of the unwanted modes can be weakened even suppressed, simultaneously the desired filter property can be obtained, and the most importance is that filter operation frequency and band are tunable without requiring to change the dielectric substrate and patch size. According to the above principle, new miniature bandpass filters with tunable operation by using single patch triangular resonators are designed, and all have low passband insertion losses and high selectivity. For each of our design, the patch defection size is fixed.

2. RESONANT PERFORMANCE OF EQUILATERAL TRIANGULAR RESONATOR

Microstrip triangular resonator has important applications in microwave circuits, especially the equilateral one, which has exact solving methods. For TM mode in an equilateral triangular resonator, the electromagnetic field patterns have no variation along the thickness direction, and electric field component E_z satisfies the 2-D Helmholtz equation

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+k_{m,n,l}^2\right)E_z=0, \quad k_{m,n,l}=\frac{4\pi}{3a}\sqrt{m^2+mn+n^2} \tag{1}$$

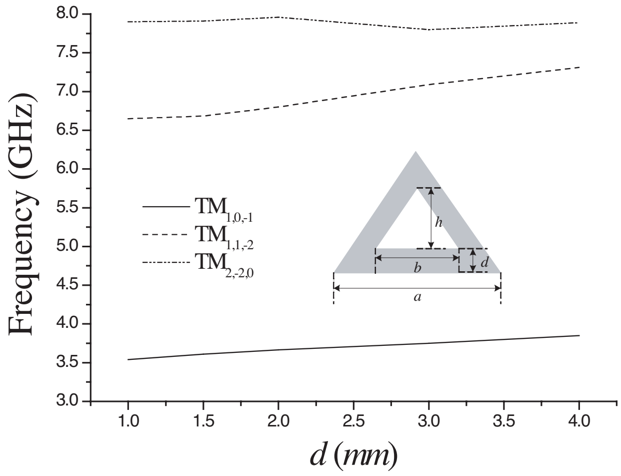
where, a is triangle side length, m and n are integers that determine the resonant mode, and $m+n+l=0$. The electromagnetic field components can be written as

$$\begin{aligned} E_z &= A_{m,n}T(x,y), \quad H_x = \frac{j}{\omega\mu_0\mu_r}\frac{\partial E_z}{\partial y}, \\ H_y &= \frac{-j}{\omega\mu_0\mu_r}\frac{\partial E_z}{\partial x}, \quad E_x = E_y = H_z = 0 \end{aligned} \tag{2}$$

The resonant frequency for the dominant mode $\mathrm{TM}_{1,0,-1}$ and higher order modes can be expressed as

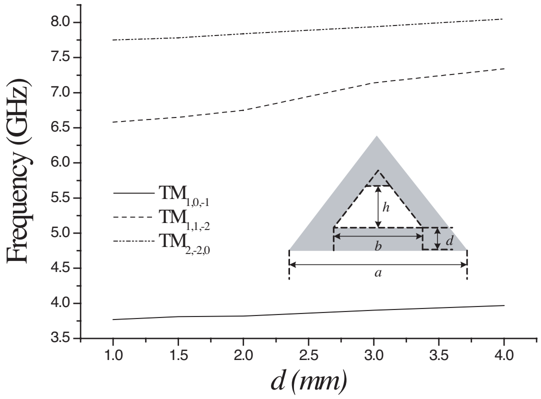
$$f_{1,0,-1} = \frac{2c}{3a\sqrt{\varepsilon_r}}, \quad f_{m,n,l} = f_{1,0,-1}\sqrt{m^2+mn+n^2} \tag{3}$$

where, c is wave velocity in free space, ε_r is the relative dielectric coefficient of substrate. The above resonant equations are important guidelines for filter design. It can be calculated that for an equilateral triangular resonator with $\varepsilon_r = 9.8$ and $a = 15\,\mathrm{mm}$, resonant frequencies of the dominant mode $\mathrm{TM}_{1,0,-1}$ and the first higher order mode $\mathrm{TM}_{1,1,-2}$ are 4.26 GHz and 7.38 GHz, respectively. If a perturbation is introduced, resonant frequencies may be fluctuated. Calculated resonant performances of the equilateral triangular resonators with patch defection are shown in Fig. 1–Fig. 3, it can be seen resonant frequency of the perturbed resonator is lower than the integrated one, and resonant frequencies of the dominant mode $\mathrm{TM}_{1,0,-1}$ and



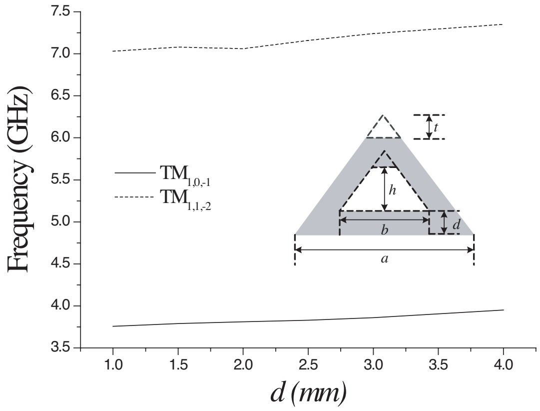
($\varepsilon_r = 9.8$, $a = 15\,\mathrm{mm}$, $b = 8\,\mathrm{mm}$, $h = 6\,\mathrm{mm}$)

Figure 1. Resonant property of the equilateral triangular resonator with fractal defection.



($\varepsilon_r = 9.8$, $a = 15\,\text{mm}$, $b = 8\,\text{mm}$, $h = 4\,\text{mm}$)

Figure 2. Resonant property of the equilateral triangular resonator with trapezoidal defection.



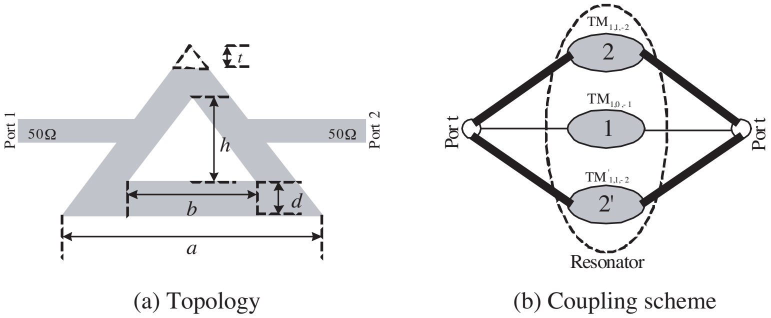
($\varepsilon_r = 9.8$, $a = 15\,\text{mm}$, $b = 8\,\text{mm}$, $h = 4\,\text{mm}$, $t = 3\,\text{mm}$)

Figure 3. Resonant property of the equilateral triangular resonator with trapezoidal defection and top triangle cut.

the first higher order mode $\text{TM}_{1,1,-2}$ increase with d increasing, and the resonant frequency distance between $\text{TM}_{1,0,-1}$ mode and $\text{TM}_{1,1,-2}$ mode are much wider than that between mode $\text{TM}_{1,1,-2}$ and the second higher order mode $\text{TM}_{2,-2,0}$. Where, d is the distance between hemlines of patch defection and equilateral triangle, and its variation introduces the changing of circuit capacitance, which brings the variation of resonant frequencies. In the research we find the closer resonant modes can be applied for implementing a multi-mode resonator filter, and the tunable fractal structure is easy for the first higher order mode splitting which brings $\mathrm{TM}_{1,1,-2}$ degenerate mode. On the other hand, resonances of $\mathrm{TM}_{1,1,-2}$ degenerate mode and $\mathrm{TM}_{2,-2,0}$ mode can be suppressed in some situations when d varying, and all these provide new ideas for filter design.

3. NEW DESIGN OF TRIANGULAR PATCH RESONATOR BANDPASS FILTER WITH TUNABLE OPERATION

For an equilateral triangular resonator bandpass filter implementation with the dominant mode $\mathrm{TM}_{1,0,-1}$ operation, the neighboring higher order mode responses should be weakened or suppressed. And for the first higher order mode $\mathrm{TM}_{1,1,-2}$ operation, response of the neighboring dominant mode ought to be weakened even suppressed in order to minimize the interference, and response of $\mathrm{TM}_{2,-2,0}$ mode must be suppressed for it too closes with the operation mode, which will bring more interference. In our design, patch fractal defection with certain feed method is introduced, and based on the above principles, required filter performances such as the dominant mode, higher order mode, single band and dual-band operation can be obtained by controlling the defection location. All of the filters are designed on ceramic substrate with relative dielectric constant of 9.8 and thickness of 1.27 mm, and patch geometric parameters are $a = 15$ mm, $b = 8$ mm. I/O feed lines that set at the middle of triangle bevel edge are microstrip lines with characteristic impedance of 50 Ω. The first designed equilateral triangular resonator bandpass filter with tunable operation is shown in Fig. 4, and coupling scheme is shown in Fig. 4(b), where, the deep dark



(a) Topology (b) Coupling scheme

Figure 4. Equilateral triangular resonator bandpass filter with tunable operation.

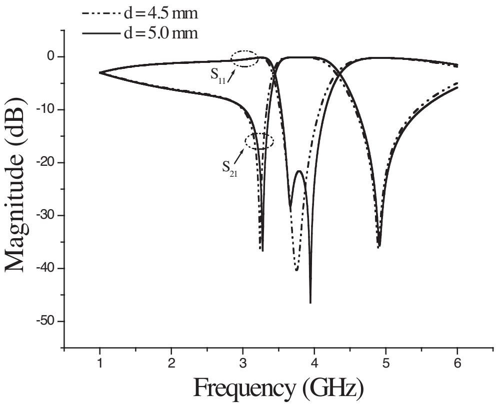
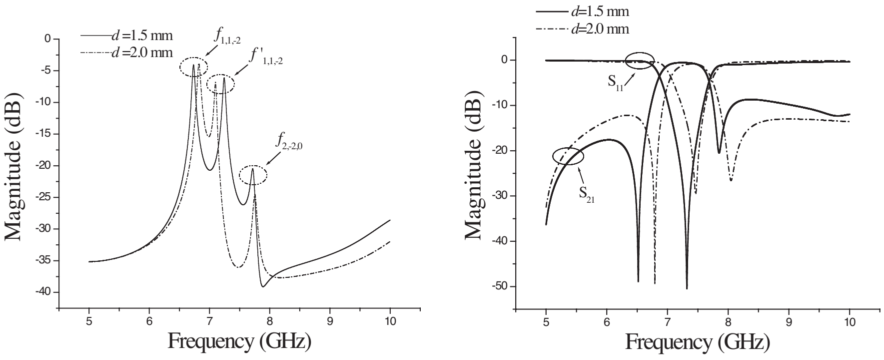


Figure 5. Frequency responses of the bandpass filter with dominant mode operation.



(a) Resonance (b) Frequency responses

Figure 6. Resonant performance and frequency responses of the bandpass filter with higher order modes operation.

lines denote coupling path of higher order dual-mode operation, while the dominant mode path is denoted by light dark lines. Simulated frequency responses are shown in Fig. 5–Fig. 7. It can be seen the filter operates at the dominant mode when $d \geq 4.5\,\text{mm}$, and the first higher order mode operation is greatly weakened. The filter possesses a center frequency of 3.85 GHz with maximum passband insertion loss of 0.21 dB, a relative bandwidth of 23.4%, and a pair of transmission zeros as well. The operation frequency shift is due to the perturbation. When $d \leq 2.0\,\text{mm}$, the dominant mode operation is greatly weakened, and the filter operates at the higher order modes, as Fig. 6 shows. It can be seen from Fig. 6(a) that $\mathrm{TM}_{1,1,-2}$ mode is splitted by the fractal defection perturbation, and operation of the neighboring $\mathrm{TM}_{2,-2,0}$ mode is suppressed and becomes very weak, so the designed filter can be seen with multi-mode operation, however, dominantly operates at the higher order dual-mode, Fig. 4 shows the filter coupling structure. It can be seen from Fig. 6(b) that the higher order modes coupling filter possesses transmission zeros at both sides of passband, low passband insertion loss of no more than 0.6 dB, and wide stopbands of more than 1.5 GHz. When $d = 1.5\,\mathrm{mm}$, the filter centers at 7.27 GHz, and has a relative bandwidth of 11.3%. When more perturbation such as a top triangle cut is introduced, filter operates at the higher order modes and bandwidth can be extended, as shown in Fig. 7. It can be seen that centers at a higher frequency of 7.62 GHz, the bandpass filter is provided with a wider passband with relative bandwidth of about 13.8%, and wider stopbands of more than 3 GHz.

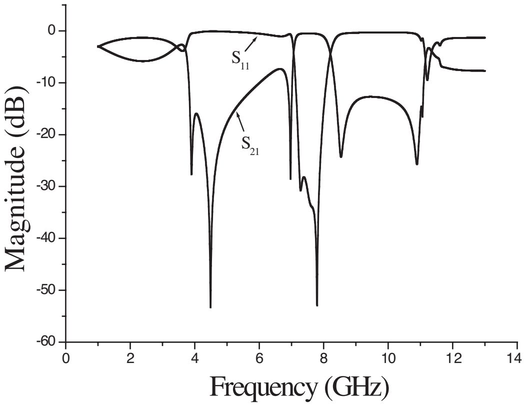
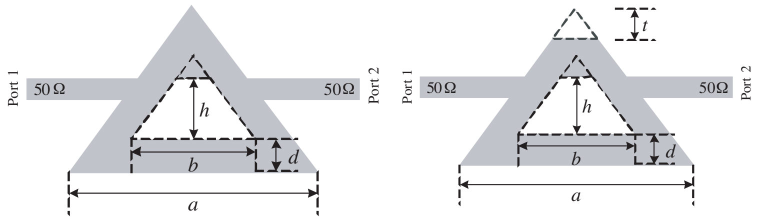


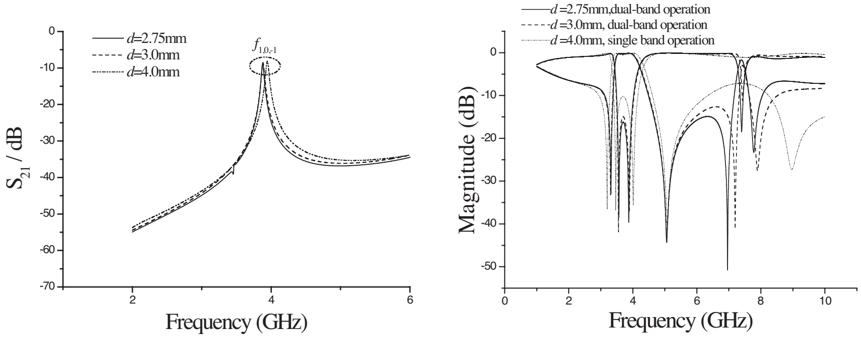
Figure 7. Frequency responses of the higher order modes operation for the triangular resonator bandpass filter with top triangle cut ($d = 1.5\,\mathrm{mm}$, $t = 2\,\mathrm{mm}$).

Two types of modified bandpass filters with tunable operation are also presented, as shown in Fig. 8, and single band, dual-band, multi-mode operation are implemented due to the modified perturbation, and the dielectric material and height are the same as the first designed filter. For the bandpass filter as shown in Fig. 8(a), dual-passband with operation frequencies of 3.8 GHz and 7.4 GHz ($f_{02} \approx 1.95 f_{01}$) is introduced when $d = 2.75\,\mathrm{mm}$, and the second band is suppressed when d increases to 4 mm, as shown in Fig. 9. For the bandpass filter as shown in Fig. 8(b), the dominant mode operation suppression, low passband insertion loss, and higher order multi-mode of $\mathrm{TM}_{1,1,-2}$,



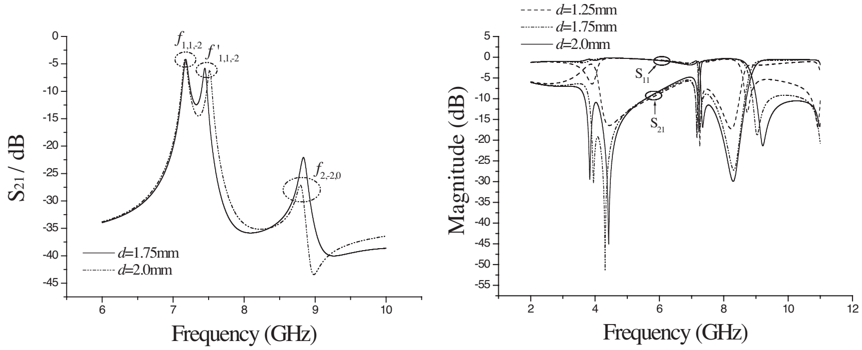
(a) (b)

Figure 8. Modified bandpass filter with tunable operation, (a) with trapezoidal defection ($h = 4\,\text{mm}$), (b) with trapezoidal defection and top triangle cut ($h = 4\,\text{mm}$, $t = 3\,\text{mm}$).



(a) (b)

Figure 9. Resonance and frequency responses of topology Fig. 8(a). (a) Dominant mode resonance of the first passband, (b) Frequency responses.



(a) (b)

Figure 10. Resonance and frequency responses of topology Fig. 8(b). (a) Higher order multi-mode resonance, (b) Frequency responses of wideband bandpass filter with multi-mode operation.

$\mathrm{TM}'_{1,1,-2}$ (degenerate mode) and $\mathrm{TM}_{2,-2,0}$ operation can be introduced when $d \geq 1.75\,\mathrm{mm}$, and the 3 dB bandwidth can be extended to about 1.6 GHz, as shown in Fig. 10. All designed filters have high frequency selectivity.

4. CONCLUSION

New patch resonator bandpass filters with tunable operation are proposed to implement wide bands, low passband insertion loss, and transmission zeros at both sides of passband as well as miniaturization. With a fractal defection as perturbation, filter operation frequency and band can be controlled, and filter performances are greatly enhanced for neighboring modes responses weakened and harmonics suppression. The new filters have small sizes, compact and simple configurations as well as high performances, and the interesting new design is very useful for microwave/RF circuit application.

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