Compact bandpass filter based on single isosceles right triangular substrate integrated waveguide cavity and modified complementary compact microstrip resonant cell

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Abstract An isosceles right triangular Substrate integrated waveguide cavity is presented. By etching the modified complementary compact microstrip resonant cell on the metal upper surface of isosceles right triangular SIW cavity, different bandpass filters are realized by using different feed ports. The triangular SIW bandpass filter with two right-angle sides as feed ports is designed and implemented. The center frequency is 17.8 GHz, the fractional bandwidth is 36.52\%, the in-band insertion loss is less than 0.3 dB, and the in-band return loss is better than 20 dB. The existence of two transmission zeros in stopband significantly improves selectivity of the filter.

Keywords: triangular substrate integrated waveguide, modified complementary compact microstrip resonant cell, bandpass filter

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Since substrate integrated waveguide (SIW) was proposed, it has attracted a large number of researchers to apply it to microwave and millimeter wave communication systems because of its high Q value, low loss, and easy processing and integration \cite{1, 2, 3, 4, 5, 6, 7}. Its most common applications are filter design \cite{8, 9, 10, 11} and antenna design \cite{12, 13, 14, 15}. Different shapes of SIW cavities have been studied, such as rectangular \cite{16, 17, 18}, circular \cite{19, 20, 21}, and triangular \cite{22, 23, 24}. Compared with rectangular and circular SIW cavities, triangular SIW cavities not only have similar characteristics, but also have more compact size. In \cite{22, 23, 24}, triangular SIW cavities were used for designing filters. By using triangular SIW cavity as basic element, a series of compact bandpass filters are designed, fabricated and measured at X-band \cite{22}. The two-cavity dual-mode SIW filter and the three-cavity dual-mode SIW filter were realized by cascading two and three isosceles triangular SIW cavities with the apex angle of 120 degrees, respectively \cite{23, 24}.

The size of the filter which is designed by cascading multiple triangular SIW cavities is obviously larger than that using single triangular SIW cavity. In order to realize the miniaturization of the filter, this paper uses single triangular SIW cavity for filter design. By etching the modified complementary compact microstrip resonant cell (M-CCMRC) on the metal upper surface of the isosceles right triangular SIW cavity, a bandpass filter (BPF) is realized. First, it is studied that two right-angled sides are used as the input and output feed ports. Then, the hypotenuse used as the input and output feed ports is studied. By introducing the perturbation vias, it is found that the transmission responses of the filter change. The number of the perturbation vias is different, and the influence on the transmission responses of the filter varies.

2. Filter design

2.1 Triangular SIW cavity design

As shown in Fig. 1, an isosceles right triangular SIW cavity have been designed by three arrays of metalized via cylinders on a low-loss dielectric substrate with an electrodeposited metal coating on upper and lower surfaces. Like the rectangular SIW, the metalized via arrays constitute the electrical walls of the cavity. The diameter of metalized via hole is $d$, and the pitch between adjacent via hole is $p$. Since the isosceles right triangular SIW cavity can reduce the volume by nearly 50\% compared with the rectangular SIW cavity, it can be widely used in the miniaturization design of filters.

The field distribution of triangular SIW cavity is shown in Fig. 2, and the resonant frequency $f_0$ in this mode can be calculated using the following relation \cite{25}, which is different from the rectangular SIW cavity.

$$f_0 = \frac{c \cdot \sqrt{3}}{2 \cdot a \cdot \sqrt{\varepsilon_r}}.$$  \hspace{1cm} (1)

where $c$ is the light velocity in vacuum, $\varepsilon_r$ is the relative permittivity of the substrate, $a$ is the right-angle side length.
of the isosceles right triangular SIW cavity.

2.2 Filter design
Compact microstrip resonant cell (CMRC), as a photonic band gap (PBG) structure, has low pass and slow wave characteristics [26, 27, 28, 29, 30, 31]. The original structure is shown in Fig. 3(a). This structure is modified, and the triangular area becomes a square area. After the modification, it is shown in Fig. 3(b), and its complementary structure is shown in Fig. 3(c).

By etching these three structures on the metal upper surface of the triangular SIW respectively, the S-parameter comparison diagram between them and the original triangular substrate integrated waveguide is shown in Fig. 4. It can be found that, when the modified complementary CMRC (M-CCMRC) structure is etched on the metal upper surface of the triangular SIW, the high frequency suppression effect is more obvious, and the passband characteristic appears. So the M-CCMRC structure shown in Fig. 3(c) is used as the resonator to design the BPF in this paper.

As all know, the SIW has a high-pass characteristic and the PBG structure has a low-pass characteristic. When the M-CCMRC is etched on the metal upper surface of the triangular SIW, a passband will be formed near its resonance frequency. In order to obtain better passband characteristic, the resonant frequency of the M-CCMRC can be adjusted by appropriately adjusting the size parameters of the M-CCMRC. When the size parameters $c_0$, $h_0$, and $c_1$ of M-CCMRC are changed, the S parameters change as shown in Fig. 5.
The layout and size parameters of the final filter design are shown in Fig. 6. The triangular SIW cavity adopts CPW on two right-angle sides as the input and output feed ports. The resonator is etched on the metal upper surface of the triangular SIW and placed parallel to the hypotenuse of the triangular SIW cavity. Previous studies have shown that the stop-band suppression of single-cavity triangular SIW is poor [22]. After the resonator is introduced, the stop-band suppression performance is significantly improved.

2.3 Modified filter design
When only the positions of the input and output feed ports is changed, the triangular SIW BPF is fed on the hypotenuse of an isosceles right triangular SIW cavity. The simulation experiment found that the performance of the filter is very poor. In order to improve the performance of the filter, perturbation vias are introduced in the cavity. The perturbation via can disturb the field distribution in the cavity, thereby affecting the coupling between the resonator and the cavity, and then correspondingly affecting the transmission response of the filter. The number of perturbation vias has a significant impact on the performance of the filter, and the comparison of electromagnetic simulation results in Fig. 7 shows that, the filter performance is very poor when there is no perturbation via hole (n = 0), and the filter performance is the best when there are 3 perturbation via holes (n = 3). The layout of the filter with three additional perturbation vias is shown in the illustration in Fig. 7.

3. Fabrication and measurement
The triangular SIW BPF with two right-angle sides as feed ports is designed and implemented on the substrate of Rogers RT/Duroid 5880 with a thickness of 0.508 mm using the standard PCB process. A photograph of the fabricated filter is shown in Fig. 8(a).

The simulated and measured results for the triangular SIW BPF are shown in Fig. 8(b). Simulation results show that, the center frequency is 17.8 GHz, the fractional bandwidth (FBW) is 36.52%, the in-band insertion loss is less than 0.3 dB, and the in-band return loss is better than 20 dB. The measured in-band minimum insertion loss is about 1.0 dB. There is a discrepancy between simulated and measured results. Possible reasons for this discrepancy are the manufacturing tolerances and the loss of SMA connectors. The triangular SIW BPF has two transmission zeros (TZs). One is generated by the internal coupling of the resonator, and the other is generated by the coupling between the resonator and the waveguide. The existence of two TZs in the stopband significantly improves the selectivity of the filter.

Table I shows comparison between this work and other reported works. The proposed triangular SIW BPF with two right-angle sides as feed ports has the characteristics of high slope selectivity, low insertion loss, wide 3 dB FBW and compact size.

| Ref. | Number of triangular cavities | $f_0$ (GHz) | 3 dB FBW (%) | Insertion loss (dB) | Number of TZs |
|------|-------------------------------|-------------|--------------|--------------------|---------------|
| [22] | 2                             | 10.67       | 12.30        | 1.25               | 0             |
|      | 3                             | 11.72       | 10.80        | 1.30               | 0             |
|      | 6                             | 10.61       | 15.10        | 1.75               | 0             |
| [23] | 2                             | 14.25       | 7.02         | 2.00               | 0             |
| [24] | 3                             | 13.85       | 10.11        | 2.00               | 0             |
| This work | 1                             | 17.8        | 36.52        | 0.3                | 2             |
4. Conclusion

The M-CCMRC is presented and etched on the metal upper surface of the isosceles right triangular SIW cavity to achieve the BPF design. The triangular SIW BPF with two right-angle sides as feed ports is designed and implemented. The measured results are relatively consistent with the simulated results. The triangular SIW BPF with hypotenus as feed ports is designed and the effect of introducing additional perturbation vias on it is studied. When the additional 3 perturbation vias are introduced, the filter shows good performance. The proposed filters with center frequency of 17.8 GHz show the advantages of low insertion loss, good selectivity, wide 3 dB FBW and highly compact, which can be used in K-band microwave communication systems.

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