LETTER

A Quasi-Elliptic Response Triple-mode SIW Bandpass Filter with Controllable Transmission Zeros

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Abstract This letter reports a novel quasi-elliptic bandpass filter (BPF) using a new triple-mode circle-shaped substrate integrated waveguide (SIW) cavity. The triple-mode SIW cavity is achieved by a dual-mode circle-shaped SIW cavity with a floating capacitive-loaded metallic patch. The resonance of one higher-order mode is independently shifted to that of dual modes to form a three-pole passband. Three finite transmission zeros (FTZs) can be produced, and two of them can be controlled well by the angle between two feeding lines. For the demonstration, a prototype filter was designed, fabricated and measured. Good agreement between measured results and simulated results is observed. The proposed triple-mode SIW filter has the merits of compact size, high selectivity and controllable bandwidth as well as FTZs.

key words: Bandpass filters (BPFs), substrate integrated waveguide (SIW), triple-mode, quasi-elliptic response.

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

Compact substrate integrated waveguide (SIW) filters with high performance have been attracted a lot of attention to be designed and applied in the modern communication systems [1-7]. And some methods have been proposed to design size-reduced SIW filters to satisfy the demand. The first one is using the hybrid structures based on SIW with other planar resonator structures, such as ground coplanar waveguide (GCPW) and complementary split-ring resonator [6-12]. Compact size and finite transmission zeros (FTZs) can be achieved. However, the unload quality factors ($Q_u$) of SIW cavities are deteriorated by the special slot lines, which results in large in-band insertion loss (IL). The second one is using the incomplete mode SIW cavities, e.g., half-mode SIW (HMSIW) [13-17], quarter-mode SIW (QMSIW) [18-23], and eighth-mode SIW (EMSIW) cavities [19, 22-24]. The sizes of them can be reduced, especially in the EMSIW cavity. But the $Q_u$ of them are also reduced with reducing sizes. The third one is using dual- and triple-mode SIW cavities. Dual-/triple mode SIW cavities have better $Q_u$ when compared with the hybrid structures or incomplete-mode SIW cavities [25-31]. Dual-/triple mode SIW filters can be designed by using a single dual-/triple-mode cavity or two cascaded dual-/triple-mode cavities. The size of triple-mode SIW filter is smaller than that of dual-mode SIW filter when the same transmission poles are considered. In [28-30], triple-mode SIW cavities are proposed by using the method of ‘mode shifting’. Triple-mode SIW filters with upper stopband FTZs are designed. However, the method has the disadvantages of hardly controlling the bandwidth and poor performance of lower stopband. In [31], a triple-mode SIW filter with controllable bandwidth is proposed using QMSIW and capacitive-loaded metallic patch. However, the performance of the lower stopband is also poor due to no FTZ located at the lower stopband.

Fig.1. (a) Top view of the proposed triple-mode SIW filter, (b) the equivalent coupling scheme (S/L: source/load, 1/2: even mode TM₁₀⁄οdd mode TM₁₁₀, 3: perturbed mode TM₆₀, solid line: main coupling path, dotted line: equivalent S-L coupling), (c) side view of the triple-mode SIW cavity.

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DOI: 10.1587/elex.16.20190541
Received August 26, 2019
Accepted September 2, 2019
Publicized September 17, 2019
In this letter, a novel bandpass filter (BPF) using a new triple-mode circle-shaped SIW cavity is proposed. The triple-mode SIW cavity is achieved by a dual-mode circle-shaped SIW cavity with a floating capacitive-loaded metallic patch. The resonance of one higher-order mode is independently shifted to that of dual modes to form a three-pole passband. And one of dual modes can be controlled by the perturbation metallic vias. One lower stopband FTZ and two upper stopband FTZs can be realized to form a quasi-elliptic response. Moreover, two of three FTZs can be controlled well by the angle between two feeding lines. For the demonstration, a prototype filter with a center frequency (f₀) of 10 GHz and fractional bandwidth (FBW) of 3% was designed, fabricated and measured to verify the proposed structure.

2. Design of the proposed triple-mode filter

Fig. 1(a) shows the top view of the proposed triple-mode SIW filter, and the corresponding coupling scheme is shown in Fig. 1(b). The proposed filter is composed of two parts: a triple-mode circle-shaped SIW cavity and a pair of GCPW feeding lines.

2.1 The proposed triple-mode SIW cavity

Fig. 1(c) shows the side view of the proposed triple-mode cavity, which is composed of a circle-shaped SIW, two perturbation metallic vias and a circle-shaped capacitive loaded patch. For easy fabrication, the proposed SIW cavity is divided into two substrate layers. In this letter, the thickness of top substrate layer t₂ is fixed by 0.254 mm, and the bottom substrate layer t₁ is fixed by 0.508 mm. Thus, the total thickness of two substrate layers is 0.762 mm. All the metallic layers have a thickness of 17 μm; the substrate has dielectric constant εᵣ of 2.2 and loss tangent of 0.0009. The diameters of the triple-mode cavity and the circle-shaped capacitive-loaded patch are denoted by r₁ and r₂, respectively.

Fig. 2 shows the electric-field distributions of modes TM₀₁₀, even and odd modes TM₁₁₀, and the perturbed mode TM₀₂₀ in the proposed SIW cavity. The capacitive-loaded patch is located on the strongest electric fields of modes TM₀₁₀ and TM₀₂₀, and it is also located at null electric fields of even and odd modes TM₁₁₀. Thus, the capacitive-loaded patch can be employed to change the resonances of modes TM₀₁₀ and TM₀₂₀ with maintaining the two modes TM₁₁₀. As shown in Fig. 3, the simulated resonances with different size of capacitive-loaded patch are presented. When the size of loading patch is increased (i.e., increasing parameter r₂), the resonance of TM₀₂₀ is shifted to the that of two modes TM₁₁₀, while the resonances of the two modes are constant as expected. The perturbation metallic vias are used to adjust the resonance of odd mode TM₁₁₀. Thus, the three controllable resonances in the triple-mode SIW cavity can be adjusted well to form a passband with controllable bandwidth.

Fig. 2. Electric-field distributions (a) TM₀₁₀, (b) even mode TM₁₁₀, (c) odd mode TM₁₁₀, (d) perturbed TM₀₂₀

Fig. 3. Simulated resonant frequencies again Lₓ with other parameters fixed.

![Fig. 3](image)

Fig. 4. Simulated responses with controllable FTZs. (r₁=25.8 mm, r₂=0.25 mm, Lₓ=4.4 mm, D=1.2 mm, t₁=0.508 mm, t₂=0.254 mm)

2.2 Analysis of the proposed filter

As shown in Fig. 1(a), the angle between two feeding lines is denoted by the parameter θ, and the angle can also be adjusted flexibly. The slots with the length of Lₘ in, are used to feed the triple-mode SIW cavity. The parameters Lₘ in and θ are employed to vary the external quality factor (Qₑ) to control the bandwidth and locations of FTZs, respectively. As shown in Fig. 2(c), the odd mode TM₁₁₀ with out-of-phase at the input and output ports can provide a negative main coupling path. As shown in Fig. 2(b) and (d), the even mode TM₁₁₀ and mode TM₀₂₀ with in-phase at the input and output ports can provide positive main coupling paths. The bypass couplings using modes TM₀₁₀ and TM₂₁₀ can provide an equivalent source-load (S-L) coupling, and the sign of S-L coupling is negative which is similar to the filter in [32]. The negative sign has been verified by a synthesized coupling matrix. Based on the coupling
scheme in Fig. 1(b), three FTZs can be realized. As shown in Fig. 4, when the parameter $\theta$ is increased, the first FTZ is closed to the passband, and the third FTZ is far away from the passband, while the second one is almost constant. Thus, the parameter $\theta$ can be used to controllable the locations of FTZs.

A triple-mode SIW filter was designed using the proposed structure in Fig. 1(a). The filter has the specifications: $f_0$ of 10 GHz, FBW of 3%, return loss (RL) of 20 dB, and three FTZs located at 9.37, 10.26 and 10.88 GHz. The simulated responses are shown in Fig. 5. The synthesized responses are also shown in Fig. 5 for comparison. And the corresponding coupling matrix is shown in (1). The discrepancies of stopband rejections between the simulated and synthesized responses are attributed to the non-resonant modes (i.e., TM_{010} and TM_{210}). The main dimensions of the designed filter are given as follows: $W_0$=2.34 mm, $r_1$=25.8 mm, $r_2$=0.25 mm, $L_w$=4.4 mm, $D$=1.19 mm, $t_1$=0.508 mm, $t_2$=0.254 mm, $\theta$=110 deg.

3. Experimental Results

To verify the proposed structure, the designed triple-mode SIW filter was fabricated and measured. The comparison between the simulated and measured responses is shown in Fig. 6(a). The measured and simulated results are in good agreement with each other. The measured $f_0$, 1-dB bandwidth, in-band IL and RL are 10.03 GHz, 290 MHz (FBW of 2.9%), 1.28 dB and 17.12 dB, respectively. Three FTZs (9.42, 10.26 and 10.985 GHz) are measured as expected. The measured average $Q_u$ is about 320. The size of the designed filter is about 28 mm $\times$ 28 mm ($0.72\lambda_g \times 0.72\lambda_g$), where $\lambda_g$ is the guided wavelength at $f_0$ of SIW. The photograph of the fabricated filter is shown in Fig. 6(b).

A comparison between the proposed triple-mode SIW filter and other reported triple-mode SIW filters is presented in Table I. The proposed triple-mode SIW filter can achieve smaller size due to the resonance of the higher-mode TM_{020} is shifted to lower frequency when compared with filter in [28, 29, 31]. Compared with filters in [28, 29, 30], the proposed filter can realize a controllable bandwidth. Moreover, the proposed triple-mode filter can also realize the merits of higher $Q_u$, higher selectivity and controllable FTZs.

![Table I: Comparison with other reported triple-mode SIW filter](image)

| Ref. | $f_0$ (GHz) | N | FBW (%) | IL (dB) | $L$ | $U$ | $Q_u$ | Size ($\lambda_u \times \lambda_d$) |
|------|-------------|---|---------|--------|----|----|------|------------------|
| [28] | 6.02        | 3 | 9.9     | 0.7    | 0  | 2  | 188  | 0.89$\times$0.89 |
| [29] | 35          | 3 | 15      | 1.8    | 0  | 2  | 200  | 0.95$\times$0.95 |
| [30] | 4.67        | 3 | 38      | 0.74   | 0  | 1  | 55   | 0.71$\times$0.71 |
| [31] | 5.52        | 3 | 22      | 1.67   | 0  | 1  | 88   | 0.75$\times$0.75 |

This work: 10 $\times$ 3 $\times$ 2.9, IL = 1.28 1 2 320 0.72$\times$0.72

$f_0$: center frequency/GHz; $N$: order of filter; $\lambda_u$: guide wavelength at $f_0$ of SIW; $L$: number of the lower stopband FTZ; $U$: number of the upper stopband FTZ; IL: insertion loss/dB.

4. Conclusion

In this letter, a novel triple-mode SIW bandpass filter is proposed. The triple-mode cavity is realized by a circle-shaped SIW cavity with a capacitive-loaded patch. For the demonstration, a filter was designed, fabricated and measured to verify the proposed structure. The measured results agree well with the simulated ones. The proposed filter has the merits of small size, high selectivity, and controllable bandwidth as well as FTZs.
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IEICE Electronics Express, Vol.xx, No.xx, xx-xx