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Multi-Mode Substrate Integrated Waveguide Wideband Filter Design with Wide Stopband Rejection Using Complementary Split Ring Resonators and Defected Ground Structures

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Abstract—This paper proposes a novel wideband filter based on a quintuple-mode substrate integrated waveguide (SIW) resonator. Two metallic vias loading a rectangular SIW cavity diagonal line are used to excite five resonant modes. A pair of the complementary split ring resonators (CSRRs) etched on the top plane to further control the degenerating modes. A quintuple-mode filter is implemented based on this resonator. One transmission zero (TZ) at the lower frequency side and three TZs at the upper frequency side were obtained to improve the filter selectivity. A seven-order filter with wide stopband rejection is investigated under the use of a pair of microstrip low-pass filters (LPFs). The proposed SIW cavity filter has been designed, manufactured, and measured as an experimental example to verify the proposed concept. Simulation and measurement results agree with 49.8% of fractional bandwidth at 5.3 GHz central frequency.

1. INTRODUCTION

Recently, substrate integrated waveguide (SIW) multiple mode resonators were investigated as an important technique to design RF/microwave filters, due to their numerous advantages such as size compaction, flexible response, high selectivity, high Q-factor, low cost, and easy integration with planar circuits. The most suggested multi-mode resonators in SIW technology are the dual and triple modes resonators [1–4]. However, their narrow passband prevents their use in the modern communication system as 5G. To provide a wide passband, several high order multi-mode resonators have been proposed [5–8]. In [5], a wideband SIW filter with compact size using a U-shape slot on the metallic plate of a double SIW cavity to produce five resonant modes is investigated. Although the proposed fifth-order passband filter provides 42% fractional bandwidth, with only one TZ at the upper frequency side, the filter cannot achieve a good selective response. In [6], a quintuple-mode filter was proposed by modifying a quarter mode substrate integrated waveguide (QMSIW) resonator. This filter provided a sharp selectivity with four TZs. However, the typical bandwidth of this filter was about 22.5%. On the other hand, the filter was implemented on a multi-layer benzo-cyclo-butene (BCB), which further complicated the circuit. To expand the filtering bandwidth, a compact passband filter on a single circular SIW resonator was proposed in [7], by using an elliptical dielectric resonator (EDR). This filter offered a fractional bandwidth up to 51.7%. In [8], the proposed filter provided five reflections and two transmission zeros at the upper frequency side with fractional bandwidth up to 60%.

Most of the higher-order single-cavity filters lack a wide stopband rejection [6–8]. It is well known that defected ground structures (DGS) have a low pass characteristic [9]. Hence, it is a good concept to use this feature to improve stopband rejection [10, 11].

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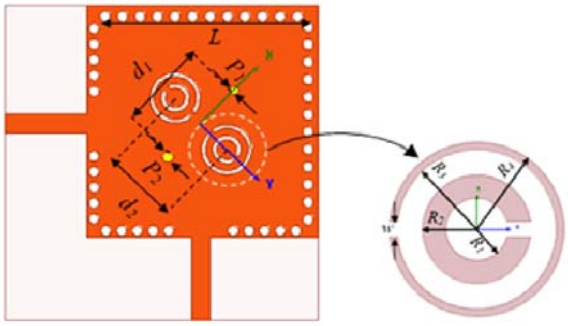
In this letter, to get a wide passband with a good selectivity as well as a wide stopband rejection, a seven-pole passband filter is proposed, designed, and implemented through a hybrid structure of a quintuple-mode SIW resonator and a low-pass microstrip filter (LPF).

2. DESIGN AND SIMULATION

2.1. Quintuple-Mode SIW Resonator Design

The proposed model of the quintuple-mode SIW resonator is shown in Figure 1(a). The resonator consists of a rectangular SIW cavity with a side length of $L = 41$ mm, implemented on a standard PCB, Rogers RO4350B substrate, with a relative dielectric constant of 3.5, dielectric loss tangent of 0.004, and thickness of 1.52 mm. The SIW cavity is perturbed by two metallic vias and a pair of CSRRs.



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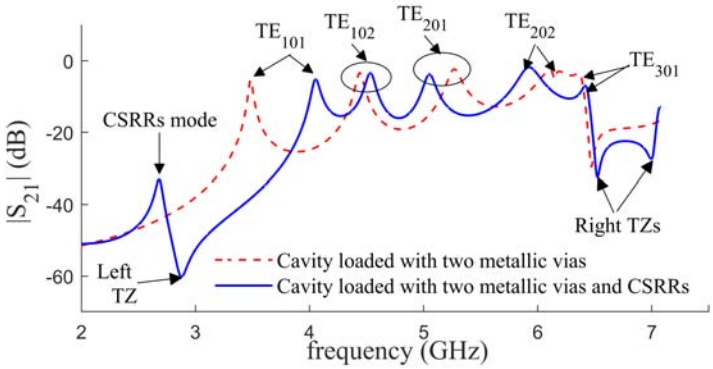


(b)

Figure 1. (a) Quintuple-mode SIW resonator and the CSRRs configuration. (b) Simulated $|S_{21}|$ of the quintuple-mode resonator-with and without CSRRs under weak coupling.

Figure 1(b) shows the simulated magnitude $|S_{21}|$ of the proposed resonator with and without CSRRs under weak coupling. Obviously, when the SIW cavity is loaded only with two metallic vias, five degenerating modes are excited, which are TE_{101} (fundamental mode), TE_{102}, TE_{201}, TE_{202}, and TE_{301} modes, respectively. Furthermore, a TZ is generated at the upper stopband. On the other hand, the fundamental mode TE_{101} is far away from the other four modes. After the integration of the CSRRs, TE_{101} is shifted near the second mode. In addition, the other four resonant modes change their frequencies, which gives a possibility to adjust the resonant frequencies and obtain flat insertion loss in the passband by modifying the CSRRs dimensions. The CSRRs are etched on the top metal of the cavity so that they mainly behave as an electric dipole, which requires an axial electrical excitation. In the proposed design, we guarantee the electrical excitation by TE_{101} within the SIW cavity. Hence, The CSRRs mode is excited below the TE_{101} mode frequency, and a TZ emerges between the two modes. Furthermore, another TZ is achieved at the upper operating band, which provides a good selectivity.

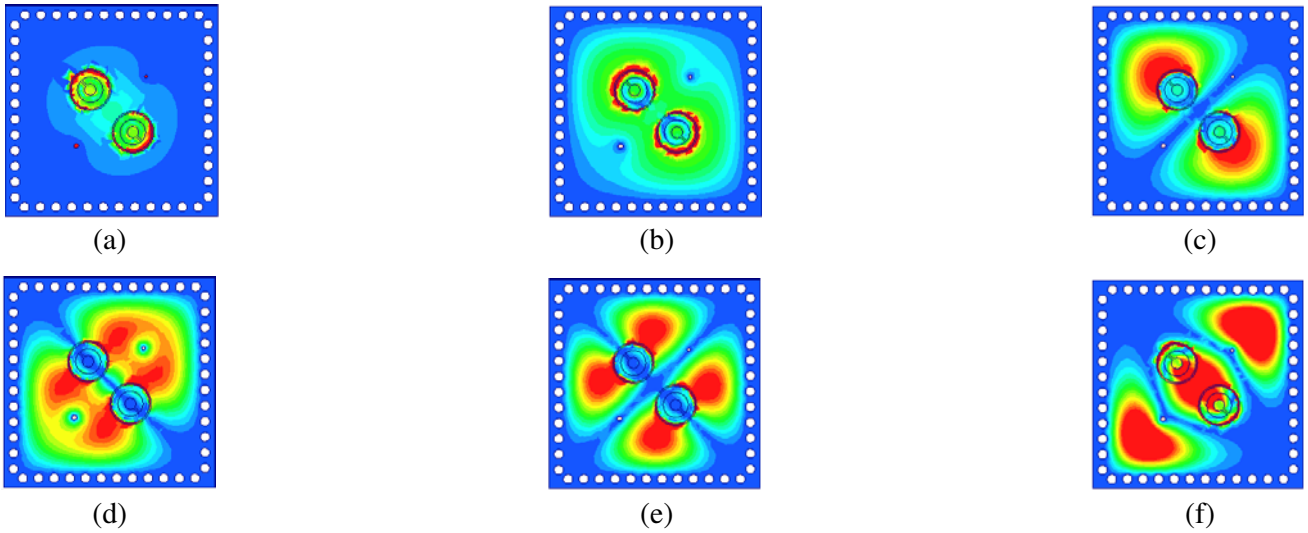
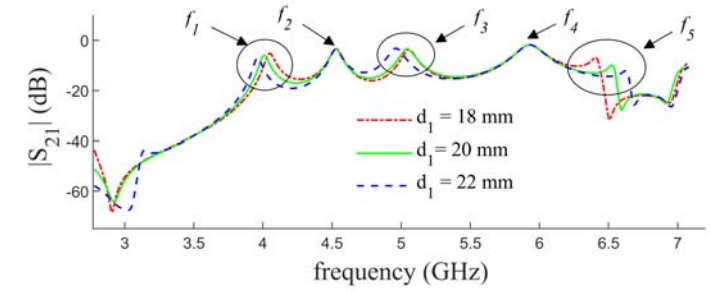


Figure 2. Electric field distributions of the first six modes in the proposed resonator. (a) CSRRs mode, (b) TE_{101}, (c) TE_{102}, (d) TE_{201}, (e) TE_{202}, (f) TE_{301}.

Figure 2 shows the electric field distributions of the five above-mentioned resonant modes and the CSRRs mode, within this cavity. It can be seen that the perturbation vias are located where the electric field of TE_{101}, TE_{201}, and TE_{301} is relatively strong. Thus, the first, third, and last frequencies can be controlled by varying the position of the metallic vias. To estimate the effect of the perturbation vias on the desired passband, the variations of the five resonant modes according to the position of the two metallic vias are plotted in Figure 3(a). Obviously, the resonant frequencies f_1 and f_5 which determine the width of the passband decrease and increase respectively with the increase of d_1, while f_2 and f_4 remain almost the same. Hence, the filter bandwidth can be adjusted by changing the perturbation vias position.

As mentioned above, the CSRRs give a possibility to control the resonant frequencies of the five



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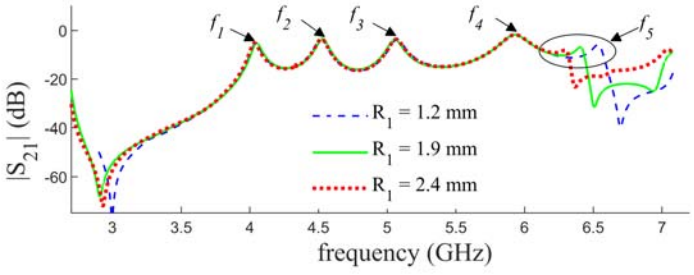

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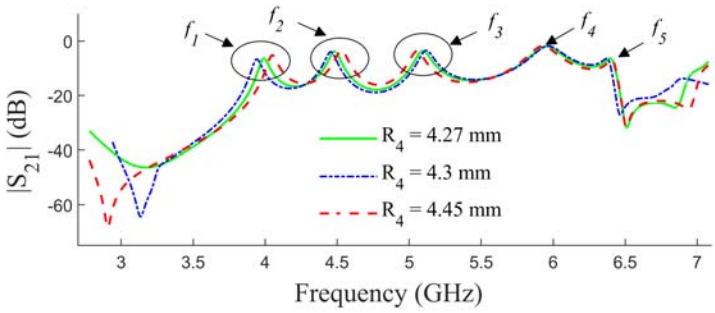
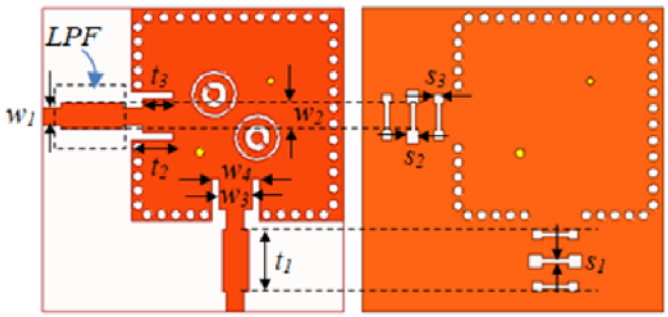


(c)

Figure 3. Resonant frequencies variation versus (a) the length d_1, (b) the radius R_1, (c) the radius R_4 under weak coupling.

degenerating modes. Depending on this property, Figures 3(b) and 3(c) show the variations of the five resonant modes by changing the CSRRs dimensions. It is observed in Figure 3(b) that the resonant frequency of TE_{301} mode becomes higher as R_1 increases while the remaining four modes are almost unchanged. Thus, the last resonant frequency can be independently tuned by the radius R_1. Figure 3(c) shows that the first, second, and third resonant frequencies become lower as the radius R_4 increases, while the fourth and fifth frequencies are slightly unchanged. Hence, the operating bandwidth between f_1 and f_3 can be effectively adjusted. On the other hand, the left TZ can be adjusted by turning the radius R_4 to provide a good selectivity.



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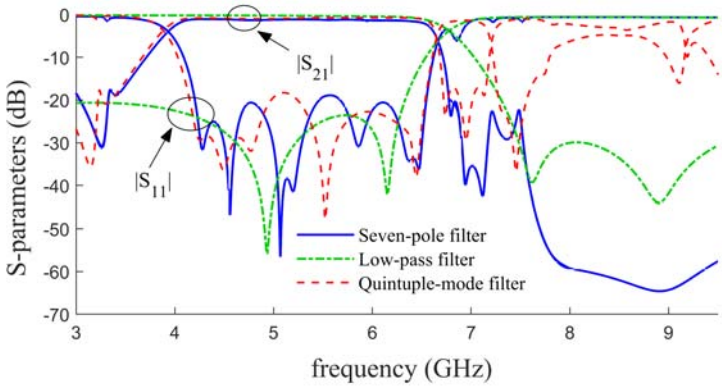

(b)

Figure 4. (a) Basic structure of the proposed multi-mode filter. (b) Quintuple-mode filter, DGS-LPF, and the seven-pole filter responses.

2.2. Design of the Seven-Order SIW Filter

Based on the proposed quintuple-mode SIW resonator, a wide passband filter is investigated in this section. The basic structure of the multi-mode filter is illustrated in Figure 4(a). A pair of triple-arrow DGSs is used with broadened transmission-line elements to achieve two identical microstrip low pass filters [9]. As can be observed in Figure 4(a), the two identical microstrip DGS-LPFs are coupled with the quintuple-mode SIW resonator, to excite the cavity and to improve the upper-band rejection. Moreover, the two slots at the end of the input/output fed lines are used to obtain strong coupling between the quintuple-mode SIW cavity and the microstrip lines.

To demonstrate the overall performance of the proposed filter, Figure 4(b) includes the comparison among three S-parameters, which are: 1) the response of the proposed quintuple-mode filter (without DGS-LPF); 2) the response of the microstrip DGS-LPF; and 3) the response of the resulting multi-mode filter (with DGS-LPF). As can be seen, the filter without DGS-LPF provides five reflections and four TZs. It is noted that an additional TZ is generated at the upper stopband. This is due to the perturbation of the coupling slots on the higher order modes in the multi-mode cavity. However, the -15 dB upper-band rejection is from 6.7 to 7.15 GHz. Hence, the DGS-LPF is optimized to obtain its cutoff frequency at 6.7 GHz. The response of the low-pass filter is plotted by the green dot-dashed curve. Obviously, the DGS-LPF has two reflections in the desired passband. Thus, the coupling between the low-pass and quintuple-mode filters produces a hybrid filter with wide passband, seven reflections, selective response, and good upper-band rejection.

2.3. Seven-Pole Filter Implementation and Results

Figures 5(a) and 5(b) show photographs of the proposed quintuple-mode SIW filter and the seven-pole filter. The dimensions optimized by HFSS are (unit: mm): $L = 41$, $R_1 = 1.19$, $R_2 = 2.7$, $R_3 = 4.1$, $R_4 = 4.45$, $d_1 = 21$, $d_2 = 12.8$, $t_1 = 11.1$, $t_2 = 8.7$, $t_3 = 6.4$, $w_1 = 3.6$, $w_2 = 4.6$, $p_1 = 0.5$, $p_2 = 0.35$, $w_3 = 7.04$, $w_4 = 9.24$, $s_1 = 0.33$, $s_2 = 2$, $s_3 = 1.6$. The simulated and measured scattering parameters of the multi-mode filter with DGS-LPF are plotted in Figure 5(c), and they are in good agreement with each other. In particular, we can see that the wide out-of-band rejection is achieved compared with the quintuple-mode filter (without DGS-LPF) response which has a narrow stopband rejection. Furthermore, the good selectivity has been obtained with the help of four TZs in the lower and upper bands. The upper-band rejection is better than 20 dB from 6.9 to 12.3 GHz. Meanwhile, the insertion loss is found about 1.67 dB; the return loss is better than 15.7 dB; and the fractional bandwidth is about 49.8% at 5.3 GHz central frequency. The group delay for the proposed filter is also shown in Figure 5(c), and its constant value in the range of 3.4–6.5 GHz is less than 0.23 ns.

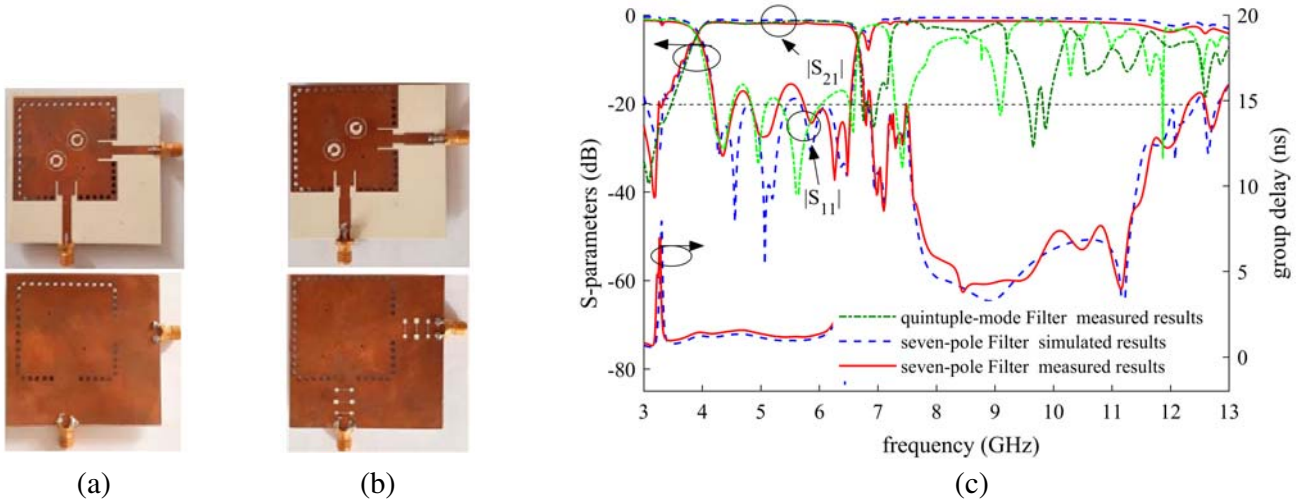

Figure 5. (a) Photography of the fabricated quintuple-mode filter. (b) Photography of the fabricated seven-pole filter. (c) S-parameters of the proposed filters and group delay of the seven-pole filter.

Table 1. Comparison with others quintuple-mode SIW filters.

Filters	Order	IL (dB)	FBW (%)	TZs	Upper-band rejection
[5]	5	< 1.1	42	1	10.35–15 GHz (20 dB)
[6]	5	< 1.9	22.5	4	-
[7]	5	< 1.17	51.7	5	-
[8]	5	-	60	2	-
[Filter without DGS-LPF]	5	< 1.53	49.8	4	6.7–7.15 GHz (15 dB)
[Filter with DGS-LPF]	7	< 1.67	49.8	4	6.9–12.3 GHz (20 dB)

Table 1 demonstrates a comparison study of the performance of some recently published high order multi-mode SIW cavity filters and the present work. Through this comparison, the proposed seven-pole filter provides a high filtering performance, in terms of good selectivity, wide passband, low loss, and better out of band rejection.

3. CONCLUSIONS

This letter presents a synthesized wide pass-band filter based on a single multi-mode SIW resonator by using two metallic vias and a pair of CSRRs for mode perturbation. The operating principle and design procedure have been discussed. Four TZs are generated to provide good selectivity. The proposed seven-order filter is created using the DGS-LPF in the feedlines section. Hence, a wide stopband rejection is achieved using DGS-LPF. The proposed candidate demonstrates that it can be used for future 5G applications considering the bandwidth of 49.8% GHz, good stopband rejection, and low loss.

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