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NOVEL DUAL MODE SUBSTRATE INTEGRATED WAVEGUIDE BAND-PASS FILTERS

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Abstract—Two novel compact substrate integrated waveguide (SIW) band-pass filters are presented in this work. They operate in dual mode at 5.8 GHz with high selectivity of a relative bandwidth of 2% and 5%, respectively. The filter has the dimension of $\lambda g \times 0.6\lambda g$, which is about 60% of a conventional SIW dual-mode band-pass filter. Simulation and measurements agree well. The empirical design formulae are presented as well.

1. INTRODUCTION

Substrate integrated waveguide (SIW) has many advantages such as higher Q-factor compared to microstrip lines and small size, light weight, and easy integration in comparison to standard metal waveguide. Since SIWs was proposed in 1998 [1], SIWs have found many applications in various microwave circuits [2]. A lot of conventional passive microwave components and devices, such as antennas [3], directional couplers [4], diplexers [5] and phase shifters [6] have been successfully realized with SIWs. Filters based on this technique have been investigated by many researchers [7–14], and some of them [10–14] make use of quasi-waveguide cavity resonant modes. SIWs can be directly integrated into microwave circuits to reduce its overall size, weight, and cost. Meanwhile, they have greatly enhanced manufacturing repeatability and reliability [12].

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Most SIW filters operate at very high center frequencies [7, 11–13], e.g., 20 GHz or higher. The overall size of a SIW filter keeps compact enough to work with other components and exhibits good performances, even when the filter is resonant at high-order modes. However, a SIW filter is mostly not acceptable even with low-order modes, such as TE_{201} and TE_{102}, when the center frequency goes down to several GHz due to its increasing size. Thus, SIWs are not suitable to work as microstrip lines in [15].

This work focuses on compact SIW band-pass filters working at dual mode with high selectivity. High selectivity and broad stop-band are important characteristics in filter designs [16–18]. We present a method to design and realize a compact SIW band-pass filter, in which a hole in the top metallic surface of the SIW filter is applied to mode regulation. Two SIW band-pass filters at 5.8 GHz with a fractional bandwidth of 2% and 5% are demonstrated. The measured results of the fabricated SIW filter agree well with simulations. The size of the proposed SIW filter is roughly about half of a traditional dual-mode SIW filter, e.g., with TE_{201} and TE_{102} modes.

2. PRINCIPLE

A SIW is a type of dielectric-filled waveguide, which is synthesized in a planar substrate with linear arrays of metallic vias. Its fabrication is done in an easy way similar to a microstrip circuit. It works in the TE modes, instead of the quasi-TEM mode of a microstrip line. Thus, some extra transitions are usually required at both input and output of a SIW band-pass filter. Planar structures, such as microstrip lines and coplanar waveguides (CPWs), may be connected to SIWs by various transitions. In this way, an SIW filter is compact and convenient to connect with other components.

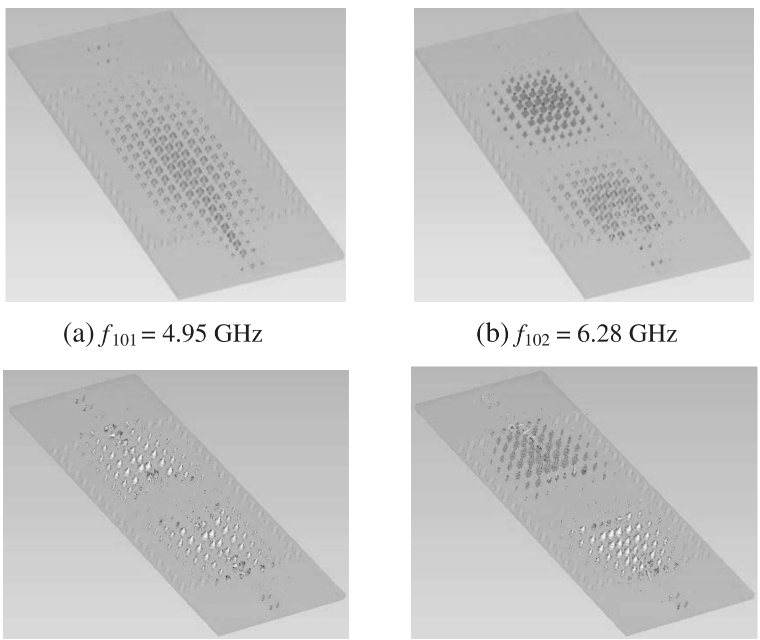
2.1. Dual Mode Filter

A section of SIW at a given boundary condition is equivalent to a cavity resonator. The resonant frequencies are

$$f_{m0n} = \frac{1}{2\sqrt{\varepsilon \cdot \mu}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \tag{1}$$

where ε and μ are the permittivity and permeability of the substrate, m and n are non-negative integers, and a and b are the effective lengths of the width and length of the waveguide, respectively. The resonant frequencies correspond to different electromagnetic field distributions and modes. The electric field distribution for the resonance modes of TE_{101} and TE_{102} are shown in Figs. 1(a) and (b), respectively.

For the novel filter, we have now introduced a circular hole etched in the top metal layer of the SIW filter to perturb the electromagnetic field distributions of these two modes and to form a highly selective band-pass filter. The top-side layout of the proposed filter is shown in Fig. 2(a). The relation between $|S_{21}|$ and the hole radius R_c is shown in Fig. 2(b). It can be seen that with increasing R_c, the resonance frequencies f_{101} and f_{102} of TE_{101} and TE_{102} get closer to each other gradually. When the frequency gap between f_{101} and f_{102} vanishes, the SIW cavity is resonant at a dual mode. The center of the resonator serves as either an open circuit in TE_{101} or a short circuit in TE_{102}. Moreover, the introduced circular hole reduces the size of the resonator by increase the resonant frequency f_{101}. The final field distribution at two frequencies in pass-band around the center frequency is shown in Figs. 1(c) and (d).

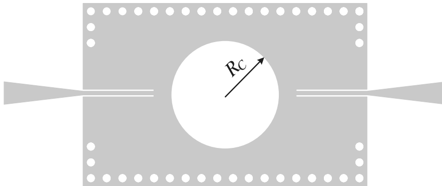


(a) $f_{101} = 4.95$ GHz (b) $f_{102} = 6.28$ GHz

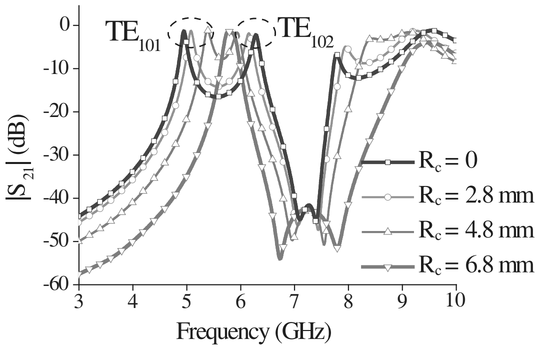
(c) $f_{101} = 5.74$ GHz (d) $f_{102} = 5.89$ GHz

Figure 1. Simulated electric field distributions of TE_{101} and TE_{102} modes.

In some dual mode SIW filter designs, e.g., with TE_{102} and TE_{201},



(a) Top-side layout of the SIW filter



(b) Resonant frequencies of TE_{101} and TE_{102} modes

Figure 2. SIW filter model and simulation results.

the width and length are almost the same [10]. The proposed dual-mode SIW filter is only about half of that one.

2.2. Introduction of an Extra Transmission Zero

A valid method is to use the transitions between SIW and microstrip lines to introduce a transmission zero. The extra transmission zero can improve the selectivity of the SIW band-pass filter. Two sections of Conductor Backed Coplanar Waveguide (CBCPW) are used to connect the SIW resonator to microstrip lines. The CBCPW transitions work as chokes at a given frequency, when the CBCPW length is about quarter-wavelength. There is a short circuit formed at the end of the CBCPW from the current simulation results. It leads to a strong reflection from the choke, and forms a transmission zero. Thus, the CBCPW transition can be used as a band-stop structure in SIW filters to introduce an extra transmission zero, of which the frequency is dependent on the length of the CBCPW transition. This is a compact design without occupy extra space. Thus, the CBCPW transitions are used in the proposed SIW band-pass filter design to improve its performance.

3. GENERIC BAND-PASS FILTER DESIGN

The SIW band-pass filter works in dual-mode with a circular hole etched on top metal layer and two CBCPW sections, as shown in Fig. 3. We first design the SIW filter prototype with roughly estimated parameters at the center frequency f_0. Then, we use CST to simulate and optimize the filter prototype. Finally, we give the following empirical formulae to help the design of the proposed SIW band-pass filter whose relative bandwidth is about 5% (The thickness of the substrate is 1 mm.):

$$W_{SIW} = \frac{0.6c}{f_0\sqrt{\varepsilon_r}} \tag{2}$$

$$L_{SIW} = 1.9 \times W_{SIW} \pm 2d \tag{3}$$

$$L_{CPW} = 0.46 \times W_{SIW} \tag{4}$$

$$R_c = 0.3 \times W_{SIW} \tag{5}$$

where c is the light speed in free space, ε_r is the relative permittivity of the substrate, d is the diameter of vias, and f_0 is the center frequency of the band-pass filter. As shown in Fig. 3, metallic vias are added at corners of the SIW to reduce its insertion loss, achieve a sharper skirt and a wider stop-band. Since these vias reduce the equivalent width of the SIW, W_{SIW} should increase to maintain the resonance frequency f_0 unchanged. The diameter d of the vias and the gap s between adjacent vias are 1 mm and 2 mm, respectively. Other dimensions of the filter are given in Table 1. Larger R_c helps to get narrower pass band and steeper skirt, but leads to higher insertion loss.

Responses of full-wave simulation and measurement are shown in Fig. 4. The center frequency is 5.8 GHz and the 3-dB bandwidth is 280 MHz, which is about 5% of the center frequency. The measured return lose is better than 10 dB and the insertion is 1.8 dB in the pass

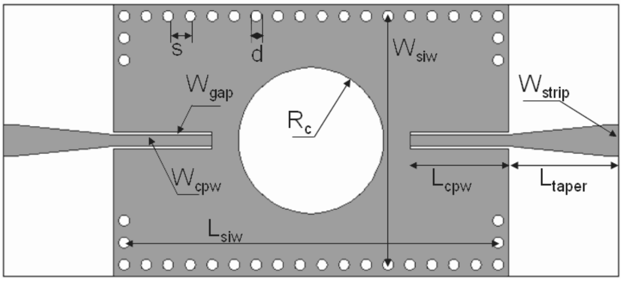


Figure 3. Dual mode band-pass filter.

Table 1. Dimensions of the filter.

Unit: mm

W_{gap}	W_{CPW}	L_{taper}	L_{CPW}	R_c	W_{SIW}	L_{SIW}	W_{strip}
0.3	0.5	10.0	9.0	6.8	22.2	34.0	2.8

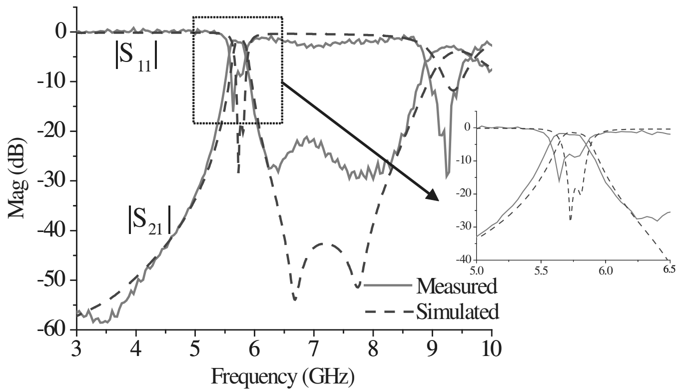
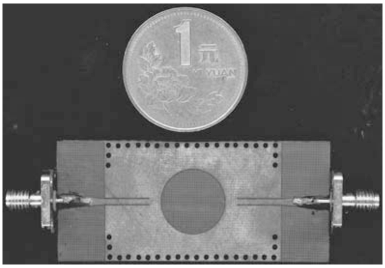
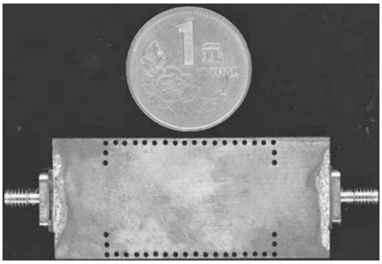


Figure 4. Simulated and measured results of the filter.



(a) Top view



(b) Bottom view

Figure 5. Fabricated SIW filter.

Table 2. Relation between losses and R_c at 5.8 GHz.

R_c (mm)	$\lvert S_{11}\rvert$	$\lvert S_{21}\rvert$	$1-\lvert S_{11}\rvert^2-\lvert S_{21}\rvert^2$
6.5	0.27	0.825	0.246
6.7	0.14	0.845	0.266
6.8	0.06	0.85	0.274
6.9	0.05	0.835	0.3
7.1	0.30	0.77	0.317

band. The fabricated filter is shown in Fig. 5.

The circular hole destroys the integrity of the SIW, from which electromagnetic power is mainly radiated. The losses of the filter consist of three parts: conductor loss, dielectric loss, and radiation loss. Small variations of the hole radius R_c contribute less to conductor and dielectric losses, but not the radiation loss. Thus, the whole loss variations can be regarded as mainly from R_c.

Table 2 shows the relationship between the loss and R_c based on simulations. It illustrates that the larger R_c is, the higher loss is. R_c should be as small as possible to reduce radiation loss. On the other side, a larger R_c helps to flat the pass band ripple.

4. HIGH SELECTIVE SIW BAND-PASS FILTER

The loaded quality factor of the SIW filter is improved to obtain a narrow pass band. We decrease the coupling coefficient between source/load and the SIW resonator by modifying the input/output coupling, which, however, leads to impedance mismatching. Two microstrip tapers are applied to both input and output ports as impedance transformers. The empirical design formulae based on electromagnetic full-wave simulation and optimization are as the followings:

$$W_{SIW} = \frac{0.6c}{f_0\sqrt{\varepsilon_r}} \tag{6}$$

$$L_{SIW} = 1.9 \times W_{SIW} \pm 2d \tag{7}$$

$$L_{CPW} = 0.26 \times W_{SIW} \tag{8}$$

$$W_{taper} = 0.38 \times W_{SIW} \tag{9}$$

$$R_c = 0.30 \times W_{SIW} \tag{10}$$

$$W_{CPW} = 0.05 \times W_{SIW} \tag{11}$$

Table 3. Dimensions of the dual-mode SIW filter.

Unit: mm

W_{taper}	W_{strip}	L_{CPW}	W_{CPW}	W_{gap}	W_{SIW}	L_{SIW}	L_{taper}
8.0	2.8	5.0	1.0	0.5	20.9	34.0	9.5

where c is the speed of light in free space, ε_r is the relative permittivity of the substrate, d is the diameter of vias, and f_0 is the center frequency of the band-pass filter.

We use the empirical formulae to design a filter prototype, and optimize it based on full-wave electromagnetic simulation (CST Microwave Studio). The larger W_{taper} is, the steeper skirt and larger pass band ripple are. On the other hand, a larger R_c helps to get a flat and narrow pass band.

The final dual-mode SIW filter structure is shown in Fig. 6, of which the center frequency is 5.8 GHz, while the introduced transmission zero is at 6.4 GHz. The filter is fabricated on F4B-2 substrate with a relative dielectric constant of 2.65 and a thickness of 1 mm. The radius of the center circular hole R_c is 7 mm. The diameter d of the vias and the gap s between adjacent vias are 1 mm and 2 mm, respectively. Other dimensions are shown in Table 3.

Measured and simulated results are shown in Fig. 7. Fig. 8 shows the fabricated filter. The filter has a 3-dB fractional bandwidth of 2%, and the insertion loss in pass band is 3.5 dB. In the proposed filter, the radiation loss cannot be disregarded as in [19]. In fact, the radiation loss plays a leading role in the insertion loss of the filter. The return loss in pass-band is greater than 15 dB. The upper parasitic pass band is suppressed below −24 dB compared to the original design in Fig. 2. The stop-band attenuation is greater than 32 dB up to 9.2 GHz. The insertion loss is higher than a generic band-pass filter design as

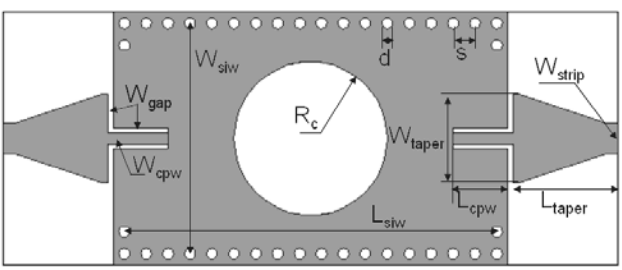


Figure 6. Highly selective dual-mode SIW filter.

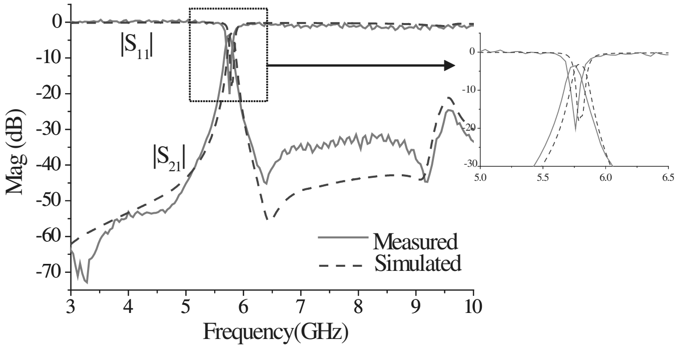
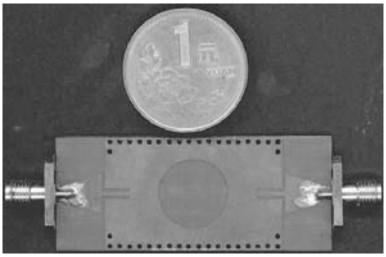
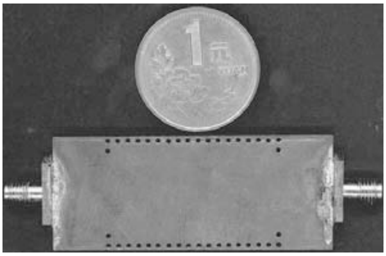


Figure 7. Measured and simulated results of the proposed filter.



(a) Top view



(b) Bottom view

Figure 8. Fabricated high selective SIW band-pass filter.

most highly selective band-pass filters do. The large insertion loss is mainly from radiation loss, which is about 1.8 dB based on simulation results. The conductor and dielectric losses are about 0.6 dB and 0.8 dB, respectively.

5. CONCLUSION

In this work, a novel dual mode SIW band-pass filter is investigated, and empirical design formulae are presented. The proposed filters work in TE_{101} and TE_{102} modes at 5.8 GHz and present attractive performances for highly selective filter applications. This design can be applied to band-pass filter with other bandwidths, e.g., 5% to 10%. Measured results are in good agreement with simulations. Usually, it is difficult for traditional SIW filters to depress the upper parasitic pass bands caused by lower- or higher-order modes [10–12]. In the proposed filter, the parasitic pass band has been depressed effectively. The size of the filter is about 60% of a traditional dual mode SIW filter that use TE_{102} and TE_{201} modes, as discussed in [10]. It is expected to find applications in microwave systems.

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