Design of a SIW-Based Microstrip Diplexer Using TM_{010} Circular Cavity

Noor Hasimah Baba, Aziati Husna Awang, M.T. Ali, M.A. Aris and Hizamel Mohd Hizan

Abstract This paper describes the application of a Substrate Integrated Waveguide (SIW) for the design of a microstrip diplexer. The diplexer is composed of two SIW circular cavity filters designed individually and combined together using a T-junction with center frequencies at 2.4 and 2.6 GHz, respectively. The working mode for the circular cavity structures is TM_{010} mode. To prove the concept, the diplexer is fabricated using Rogers RT5880 with dielectric constant, $\varepsilon_r = 2.2$ and height of substrate 1.57 mm. The performances of the proposed design are verified through both simulation and measurement.

Keywords Circular cavity · Diplexer · T-junction · Substrate Integrated Waveguide · SIW

1 Introduction

In last few decades, rapid development in communication systems such as GSM, WLAN, LTE, and satellite applications has introduced many wireless products for millimeter-wave applications. Each of these systems uses passive microwave devices to operate such as filter and diplexer. Generally, both of these devices are larger compared to other components in the system. Therefore, there will be a great interest to make these devices to become smaller and more compact. The diplexer normally composed of two filters is a two-way three-port network commonly used for separation of received and transmits signals served by a common antenna [1]. Traditional structure diplexers suffer from disadvantages such as being bulky,

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costly, and difficult to fabricate. In addition, it cannot be integrated with the mm-wave planar integrated circuits of the transceiver, and the degradation of performance can be substantial for transition from a waveguide to planar integrated circuits [2, 3].

The diplexer and its operation principle are shown in Fig. 1b. In transmitting mode, two signals with different frequencies are injected in port 1: One of them exits from port 2, while the other one from port 3. In receiving mode, ports 2 and 3 receive two different signals, which exit from port 1. Over the past decade, many works have been carried out to replace all-metallic waveguide structures with SIW circuits. Substrate Integrated Waveguide (SIW) is a type of dielectric-filled waveguide which is implemented in a planar substrate with linear arrays of metallic vias. Those vias are used to realize metal edge wall that connects the two ground planes of the substrate. The SIW offers advantages such as high Q factor, low insertion loss, low cost, and high power-handling capacity [4, 5]. Apart from the

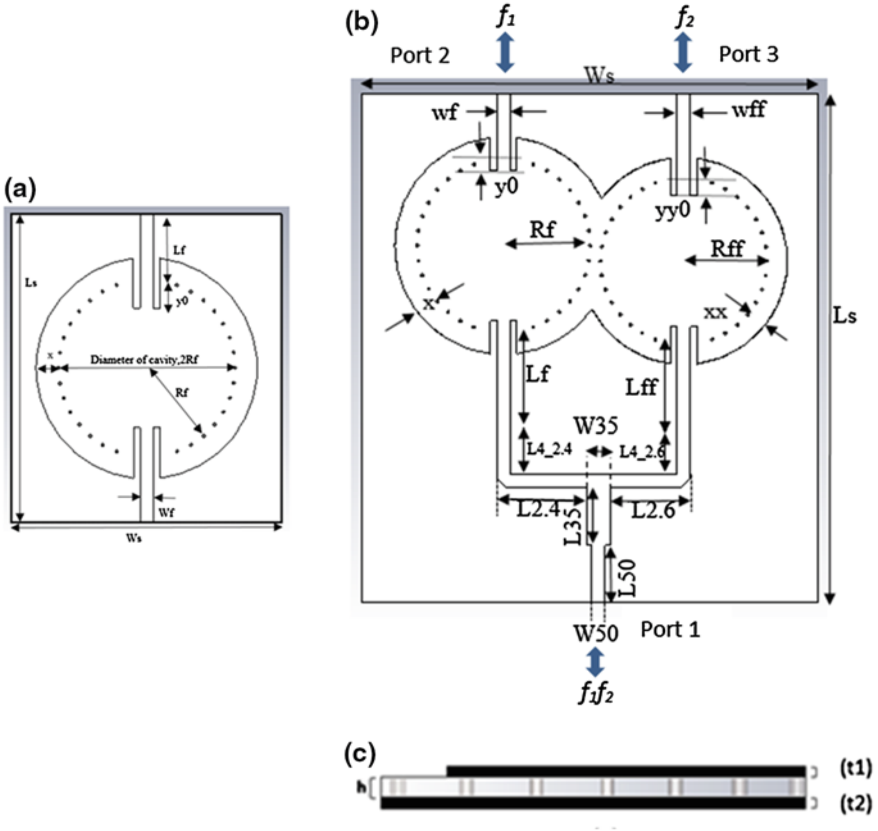


Fig. 1 **a** Top view of SIW filter **b** top and **c** cross-sectional views of SIW diplexer

well-known advantages, this technique widely appears in various conventional passive microwave components and devices such as filters, couplers, power dividers, and antennas [6–9].

2 Methodology

Initial step in designing the diplexer is to first design and simulate the individual filters satisfying the specifications desired. The two filters have been designed at center frequencies of 2.4 and 2.6 GHz, respectively. Secondly, these filters are combined together using suitable matching network. In this case, a microstrip T-junction power divider followed by a 50 Ω microstrip line with inset feed is used to directly excite the filters. Configurations of the proposed filter and diplexer with the transitions are shown in Fig. 1. The topology comprises one metallic top layer (t1), one conductive ground layer (t2), two circular cavity resonators, inset couplings, and linear arrays of via holes to form a circular via wall around the cavity resonators. Measured results are presented and compared to those simulated by 3D Electromagnetic Simulation (CST) software package.

2.1 Network Synthesis of Diplexer

To begin with, a network that meets Table 1 design specification is synthesized using standard filter theory starting with a low-pass filter prototype having Chebyshev response [10]. The equivalent circuit of the first-order diplexer is shown in Fig. 2. In this network, the admittance inverters J01 and J12 are used as the input and output coupling of the filter.

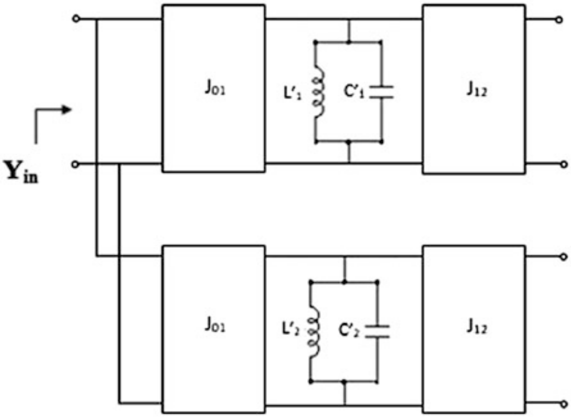
The shunt connected resonators are calculated using Eqs. (1) and (2), as shown below:

$$L_1' = \frac{1}{\alpha C_{1\omega_0}} \tag{1}$$

Table 1 First-order TM_{010} SIW filter specifications

Filter specifications	
Center frequency, f_0	2.4 and 2.6 GHz
Passband bandwidth (PBW)	20 MHz
Passband return loss (L_R)	≥10 dB
Stopband insertion loss (L_A)	>10 dB at $f_0 \pm 100$ MHz (SBW)

Fig. 2 Equivalent circuit for first-order diplexer



$$C_1^{'} = \frac{\alpha C_1}{\omega_0} \tag{2}$$

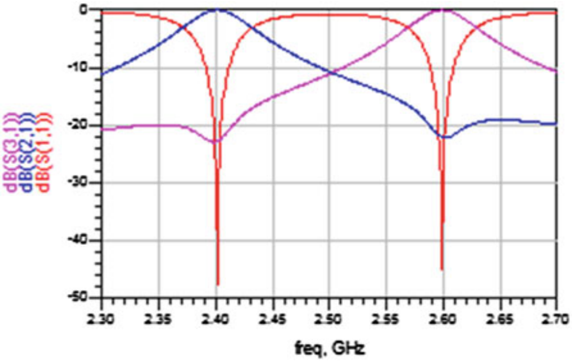
where α is the bandwidth scaling factor and ω_0 is the midband frequency. All the element values for the diplexer are shown in Table 2.

The simulated responses of the first-order diplexer having center frequencies at 2.4 and 2.6 GHz with 10 dB passband return loss bandwidth of 20 MHz are shown in Fig. 3.

Table 2 Element values for single-mode diplexer

Element	Value (2.4 GHz)	Value (2.6 GHz)
$L'_1 = L'_2$	0.8289 pH	0.7063 pH
$C'_1 = C'_2$	5.3052 nF	5.3052 nF
$J_{01} = J_{12}$	1	1

Fig. 3 Equivalent circuit simulation results



2.2 Electromagnetic Simulation

The fundamental parameter in designing the cavity of the SIW filter is the resonant frequency. The radius of the circular SIW cavity is approximated according to the resonant frequency using the following formula [10], and then the radius is optimized by electromagnetic software.

$$\left(f_r^{\text{filter}}\right)\begin{matrix}TM^z\\010\end{matrix} = \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\left(\sqrt{\frac{2.4049}{a_{\text{filter}}}}\right)^2 \tag{3}$$

where c is the speed of light in free space; μ_r is the relative permeability while ε_r is the dielectric permeability of the substrate, respectively. The value 2.4049 is the first zero of the Bessel function and a_{filter} is the radius of the SIW filter. The design rules related to the pitch and via diameters to ensure that the radiation loss is kept at negligible level are already given in [11]. In this design, the matching from 50 Ω microstrip line to the SIW cavity resonator section is achieved by the inset excitation structure which converts quasi-TEM mode propagating in microstrip line to the TM_{010} mode of the SIW cavity resonator. From the simulation, it is observed that the depth inset coupling parameter y0 of Fig. 1 is considered critical and needs to be carefully designed and optimized. Figure 4 shows the variation of the length y0 of the SIW diplexer, indicating that increasing the depth slot from 1.95 to 3.95 mm will increase the coupling and the return loss values. The optimized geometric parameter of the proposed structure is shown in Table 3.

Fig. 4 Effect of inset length y0 of SIW diplexer

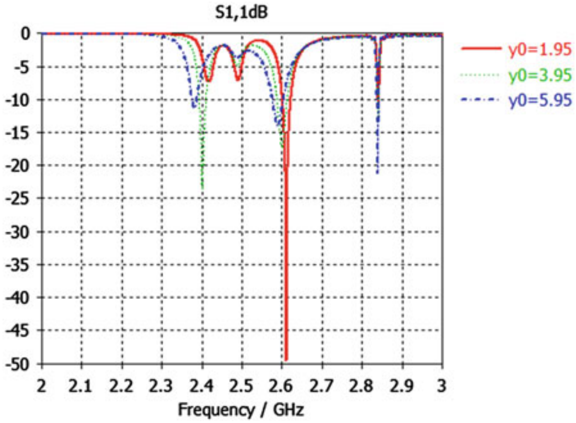


Table 3 Geometric dimensions of first-order diplexer

Symbol	2.4 GHz Value (mm)	2.6 GHz Value (mm)	Symbol	Value (mm)
Rf	30.33	29.12	*h*	1.57
wf	4.65	4.65	Ls	177.80
yo	3.96	36.36	Ws	160
y0	3.95	6.17	*t*	0.035
Lf	22.74	20.99		
x	7.81	7.21		

3 Results

To prove the concept, the diplexer structure is fabricated using RT-5880 substrate with dielectric constant, $\varepsilon_r = 2.2$ and thickness of 1.57 mm, and a photograph of the diplexer prototype is shown in Fig. 7. When measuring the S parameters of the diplexer, one port is matched with a standard 50 Ω load, and the other two ports are connected to a vector network analyzer (VNA). Figure 5 shows the simulated and measured S parameter response of 2.4 and 2.6 GHz SIW filters. The simulated and measured results of the SIW diplexer are given in Fig. 6. From this plot, the simulation return losses for the lower and upper channels are greater than 28.68 and 17.16 dB, respectively. The return losses measured at the ports remain greater than 12.24 and 17.86 dB within the associated channels. The measured minimum insertion losses show a slight deviation from 1.42 and 1.07 dB to 2.24 and 3.17 dB at each channel. Measured result shows that the frequencies for the lower and upper channels are shifted for about 30 MHz. The shifting of the frequencies is, however, considered acceptable and is probably due to errors which occurred during the fabrication process and tolerances of the substrate dielectric constant. The difference may also be due to extra loss from the SMA connectors. Consider the reasons of the errors, the presence of air gap may be the possible reason, because higher energy

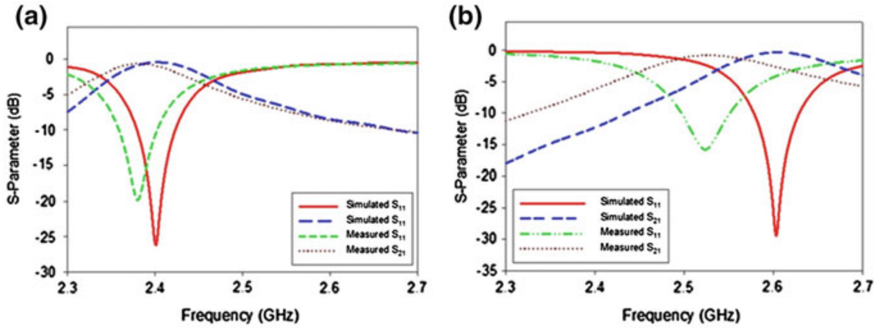


Fig. 5 **a** Simulated and measured S parameters of 2.4 GHz SIW filter **b** simulated and measured S parameters of 2.6 GHz SIW filter

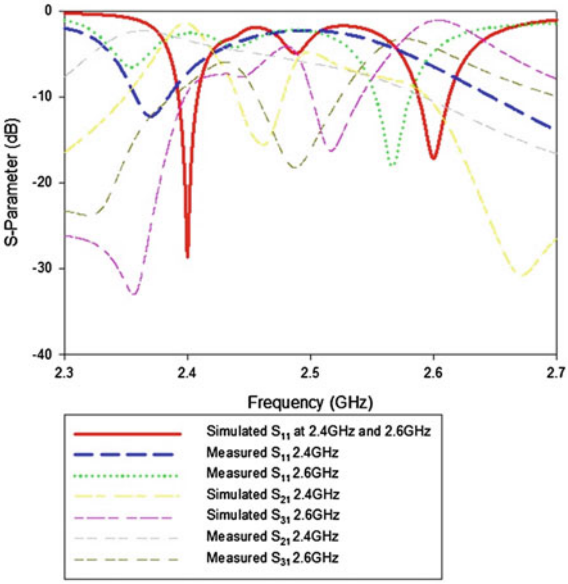


Fig. 6 Simulated and measured S parameters response of SIW diplexer

Fig. 7 Photograph of the fabricated SIW diplexer

losses affect the efficiency of the device. Also the metallic vias used were not perfect conductors and seems they have different values of dielectric, while the dielectric for PEC is infinite [12].

Figure 8 plots the measured results of the isolation between ports 2 and 3. The diplexer provides isolation better than 15 dB at both channels. This moderate performance is caused by the coupling effects that the adjacent resonators introduce. The main limitation of the SIW technology is the maximum isolation that a discontinuous wall made of via holes can provide between adjacent resonators, producing undesirable cross-couplings [13]. However, even with non-perfect isolation the design of a diplexer is possible, and with a good fabrication process, the integrated structure can give a better performance. In addition, in order to improve the response and bandwidth of the structure, higher degree of filter can be employed.

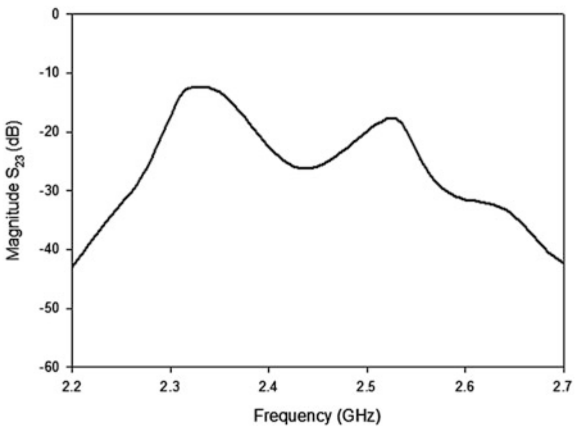


Fig. 8 Measured isolation of the SIW diplexer

4 Conclusion

A new prototype of compact SIW microstrip diplexer is proposed employing single-mode circular cavity resonators having center frequencies at 2.4 and 2.6 GHz, and which is proposed for LTE/WiFi applications. Good agreement between simulation and measurement is achieved. The diplexer features low insertion loss, compact, simple structure, and easy to connect to other circuits. This design provides an alternative solution for the uplink/downlink RF front-end subsystem that is essential for wireless communications systems.

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