Progress In Electromagnetics Research Letters, Vol. 95, 17–24, 2021

Double-Layer TM_{110} Mode of Substrate Integrated Waveguide Circular Cavity (SIWCC) for Wireless Communication Applications

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Abstract—A substrate integrated waveguide circular cavity (SIWCC) bandpass filter is developed using printed circuit board technology. A circular cavity structure using TM_{110} mode was employed in the design of the filter to operate at the frequency of 4.75 GHz, which is in the C-band frequency range. The filter was designed based on double-layer elements comprising a substrate integrated circular cavity (SICC) and a transmission line (TL) that produce single-mode resonance. In the proposed structure, circular resonators consisting of vias and a rectangular patch at the top layer are combined into a circular substrate integrated waveguide (SIW) structure. To achieve the desired resonance frequency, a triangle probe is etched at both sides of the microstrip line feeding section. The proposed structure is put in a conducting box to prevent radiation to the outside and eliminate radiation loss. Furthermore, the desired centre frequency and bandwidths of the passbands can be obtained by adjusting the dimension of the filter. To prove the concept, the filter structure is fabricated using Rogers RO4350B^{TM}circuit materials with a dielectric constant of $\varepsilon_r = 3.48$ and height of the substrate of 1.52 mm. The design was simulated using Ansoft HFSS simulator and measured using a vector network analyser. Simulation and fabrication results are compared for verification. The proposed SIWCC bandpass filter has potential applications in satellites and wireless communication systems.

1. INTRODUCTION

Recent advances in microwave filter design in the radio frequency (RF) range have been incorporated into wireless communication systems. This has stimulated the demand for higher integration, miniaturization, and improved performance, leading to a high level of electromagnetic interference. Microwave filter and antenna designs for millimeter-wave applications are highly desirable, and the basic device in the RF front-end filter has been evolved using microstrip, substrate integrated waveguide (SIW), and dielectric resonator [1, 2]. Its electrical properties characteristic decisively determines the overall performance and size of the radio front-end of a wireless base-station [3]. However, most of the high performing and specifically narrowband microwave filters use nonplanar structures because of their flexibility in realizing various coupling topologies and high-power handling capability [4]. High performance in this context is defined as low insertion loss, steepness transition, and sufficient rejection at hostile frequency bands by the most efficient use of the available volume, materials, and manufacturing process [5–7].

SIW bandpass filter has been receiving significant attention because of high performance, compact size, low loss, and easy integration with other planar technologies [8, 9]. Nevertheless, some of the conventional cavity resonators are not compatible with the millimeter-wave technology and have large

Received 6 September 2020, Accepted 17 November 2020, Scheduled 27 November 2020
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sizes [10]. In cross-coupled filter structures, magnetic and electric couplings are required to generate an electrical response. In particular, by removing the via holes between two SIW cavities, the magnetic coupling can be easy to realize. Several methods have been applied to obtain electric coupling in [11–14]. However, the applied methods suffer additional loss, low output power, resonance mode instability, and complex integration with planar technology [13].

One way to alleviate the problems is to integrate a bandpass filter and multiband bandpass filter on SIW based on circular cavity (SIWCC), which are formed using two rows of conducting vias or slots by connecting the top and bottom plates in the substrate material [14]. This study introduces a SIWCC design consisting of vias and a rectangular patch at the top layer, combined into a circular SIW structure. The triangle probe is etched on both sides of the microstrip line feeding section to ensure the filter to perform well with acceptable electrical characteristics. In this part, SIW cavity is directly excited by a 50-ohm microstrip line in a two-layer configuration, which provides a better narrowband response for the filter. Moreover, the vias are embedded in the dielectric substrate to provide simple integration within other planar devices, leading to a compact size. Therefore, this research introduces a new SIW circular cavity excitation method in which substrate circular cavity single modes were achieved at the resonant frequency of $f_r = 4.75\,\text{GHz}$ and passband bandwidth of 100 MHz at 3 dB bandwidth. The resonant frequency is chosen at 4.75 GHz, which is in the C-band frequency range and used in many satellite communication systems such as for INSAT, radar, and wireless technology. This range is in C-band frequency from 4.4 to 4.8 GHz as allocation to receive frequencies for INSAT [15]. The electromagnetic (EM) field simulations, fabrication process, and measured results are presented in the following sections to verify the proposed design.

2. SIWCC BANDPASS FILTER DESIGN AND CONFIGURATION

Figure 1 shows the bandpass equivalent circuit of the proposed filter. In the equivalent circuit, the admittance matrices J_{01} and J_{12} represent input and output admittances of the filter, respectively. The capacitor C_1' and inductor L_1' represent the single-mode resonator in the circular SIW cavity [16]. The values of the capacitor and inductor can be calculated using Equations (1) and (2) as follows.

$$C_1' = \frac{1}{\alpha C_1 \omega_0} \tag{1}$$

$$L_1' = \frac{\alpha C_1}{\omega_0} \tag{2}$$

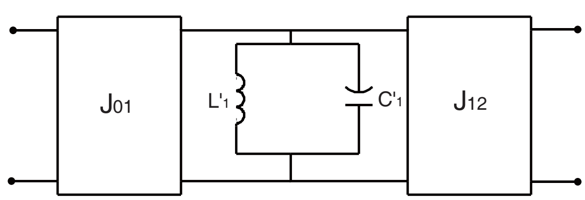
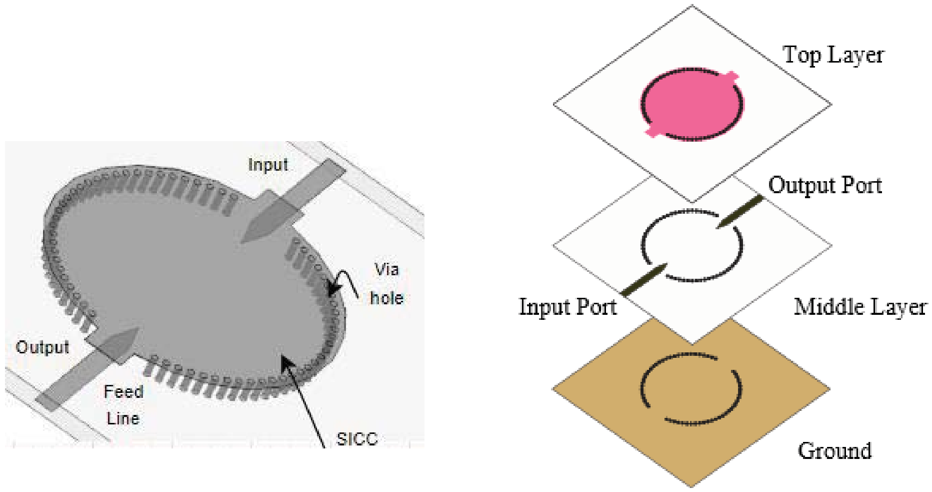


Figure 1. Equivalent circuit diagram.

The geometry of the proposed circular cavity filter illustrated in Fig. 2 consists of a double-layer substrate encompassing the SICC. The diameter of the SICC, denoted as D, is 40 mm on the top layer, and a rectangular patch is attached together with the circular shaped cavity structure. The transmission line (TL) with a triangle probe attached to the feed line is placed on the middle layer. Rogers RO4350B$^{\text{TM}}$laminates are used as substrate material with a substrate thickness of $h = 1.52\,\text{mm}$. The resonant frequency at TM_{110} mode with the dielectric constant (ε_r) of 3.48 and loss tangent ($\tan\delta$) of 0.0037 has been chosen to operate at approximately 4.75 GHz, as can be calculated using Equation (1). The resonant frequency is fixed by the diameter of the SICC, via holes diameter, and the distance between two adjacent via holes, which are imposed by technological limitations.

The resonant frequency for the circular cavity can now be calculated using the following equations [16], where f_r is the resonant frequency, a the radius of the cavity, and Δh the height of



(a) (b)

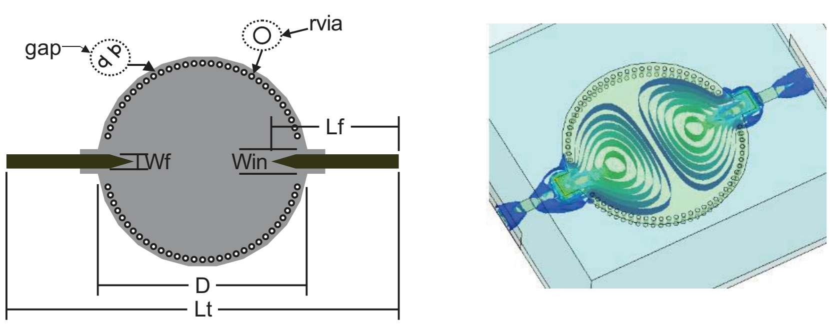
Figure 2. Geometry of the proposed circular cavity filter. (a) 3D view, (b) configuration of each layer.

the cavity. Further, c is the speed of light, and μ_r and ε_r are the relative permeability and relative permittivity of the material inside the cavity, respectively. Additionally, m, n, and p are the numbers of field variations in the standing wave pattern in the x, y, and z directions, respectively. X'_{mn} is 3.8318 for the TM_{110} mode. Equation (3) is used to determine the initial dimensions of the cavity for a desired resonant frequency in the TM_{110} mode. The related resonant frequency is determined using Equation (4).

$$(f_r)^{TM^Z}_{mnp} = \frac{1}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{x'_{mn}}{a}\right)^2 + \left(\frac{p\pi}{\Delta h}\right)^2} \tag{3}$$

$$(f_r)^{TM_{110}} = \frac{C}{\sqrt{\varepsilon_r}}\left(\frac{3.8318}{2\pi a}\right) \tag{4}$$

The SICC design includes the gap spacing between metal via holes of side walls where it is limited to less than half guided wavelength at the high frequency for the radiation losses to become negligible. The angle between two adjacent via holes is 5°. The radius of via holes is set at 0.5 mm to reduce the leakage between via walls as well as the radiation loss. Prior to design optimization, $w_{in} = w_f = 5$ mm (see Fig. 3), microstrip lines act as a feeding structure, and rectangular slot serves as the external coupling structure of the SIWCC. The triangle probes are designed to excite the field within the cavity



(a) (b)

Figure 3. Configuration of the proposed SIWCC filter: (a) Layout of the SIWCC, (b) simulated electric field distribution.

waveguide and to maximize the energy transfer so that its field pattern matches the configuration of the desired mode. The detailed geometrical parameters, as shown in Fig. 3, after optimization are as follows; $w_{in} = 5\,\mathrm{mm}$, $D = 40\,\mathrm{mm}$, $r_{via} = 0.5\,\mathrm{mm}$, $gap = 0.5\,\mathrm{mm}$, $w_f = 2.9\,\mathrm{mm}$, and length feed line $L_f = 20\,\mathrm{mm}$.

3. SIMULATION, FABRICATION, AND MEASUREMENT RESULTS

The SIWCC simulation was performed using Ansoft HFSS Software and analysed along with the EM simulation to find the exact dimension of the cavity. The coupling effect between two dual-path circular cavities is achieved by magnetic coupling between the input and output admittances of the feed lines. Therefore, to achieve better performances, the dimensions of the probe are adjusted to optimise the parameters values. In our design, many parameters such as radius of cavity, radius of via, and dimensions of the probe are used to control the frequency response of the filter. However, length (L_p) and width (w_p) of the probe are changed to see the variation of the electrical response for both return loss, S_{11} and insertion loss, S_{12}, while the rest of the dimensions are left intact. The simulation results are depicted in Figs. 4 and 5. Both figures prove that changes in the length and width of the probe would change S_{11} and S_{12} accordingly. Tables 1 and 2 show the simulation results for f_r, S_{11}, and S_{12}. With the increase in the probe dimensions, the resonant frequency and insertion loss increased slightly and shifted to the left. Furthermore, changing the length and width of the probe will change the resonance frequency and affect the frequency response. This results in higher insertion loss, and centre frequency slightly shifted which may be due to the imperfect bonding between substrate layers, mismatches in the rectangular window size, and improper alignment during the assembly process. In realization, layers were embedded tight together to form the desired multilayer structure with an air gap as shown in Fig. 7(b).

Between the length and width of the probe studied, the best choice is at the frequency 4.75 GHz.

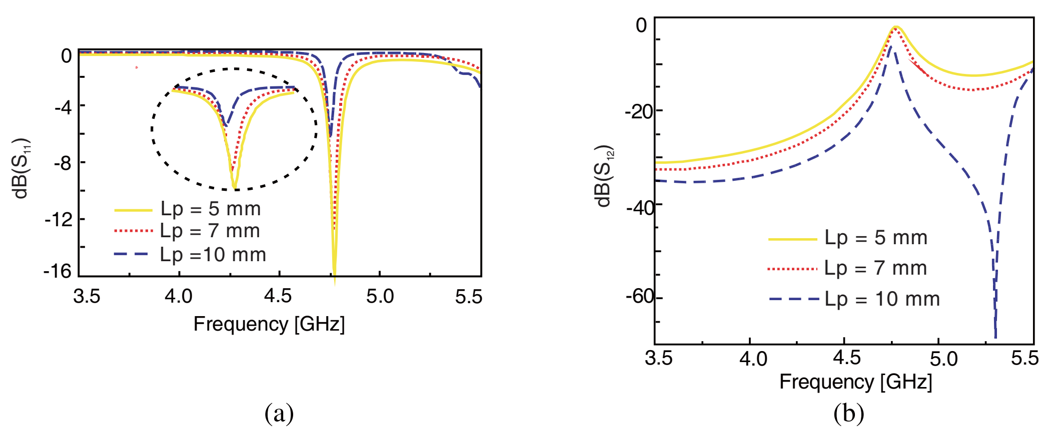


Figure 4. Effect of varying the length of the probe. (a) Return loss, S_{11}. (b) Insertion loss, S_{12}.

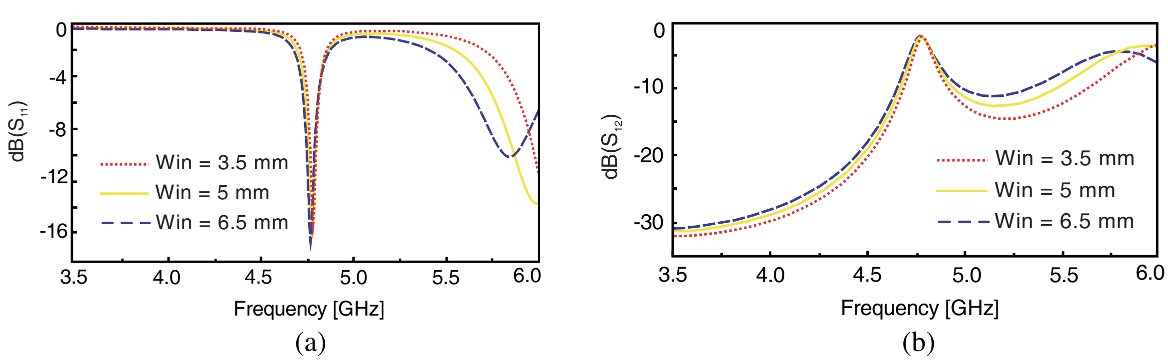


Figure 5. Effect of varying the width of the probe. (a) Return loss, S_{11}. (b) Insertion loss, S_{12}.

Table 1. Variation of the frequency response with respect to the length of the probe.

L_p (mm)	S_{11} (dB)	f_r (GHz)	S_{12} (dB)
5 mm	17 dB	4.78 GHz	−2 dB
7 mm	13 dB	4.77 GHz	−2.1 dB
10 mm	7 dB	4.76 GHz	−6.5 dB

Table 2. Variation of the frequency response with respect to the width of the probe.

W_{in} (mm)	S_{11} (dB)	f_r (GHz)	S_{12} (dB)
3.5	17	4.78	−2.0
5	15	4.76	−2.0
6.5	16	4.76	−2.0

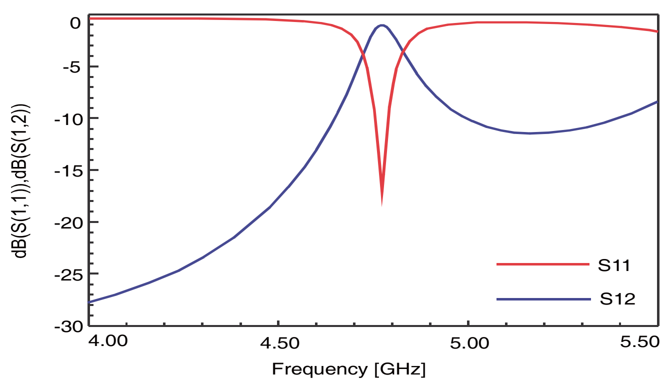


Figure 6. Simulation result of the proposed filter.

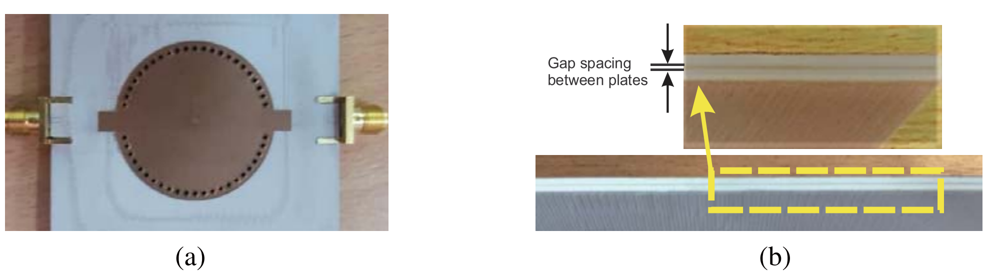


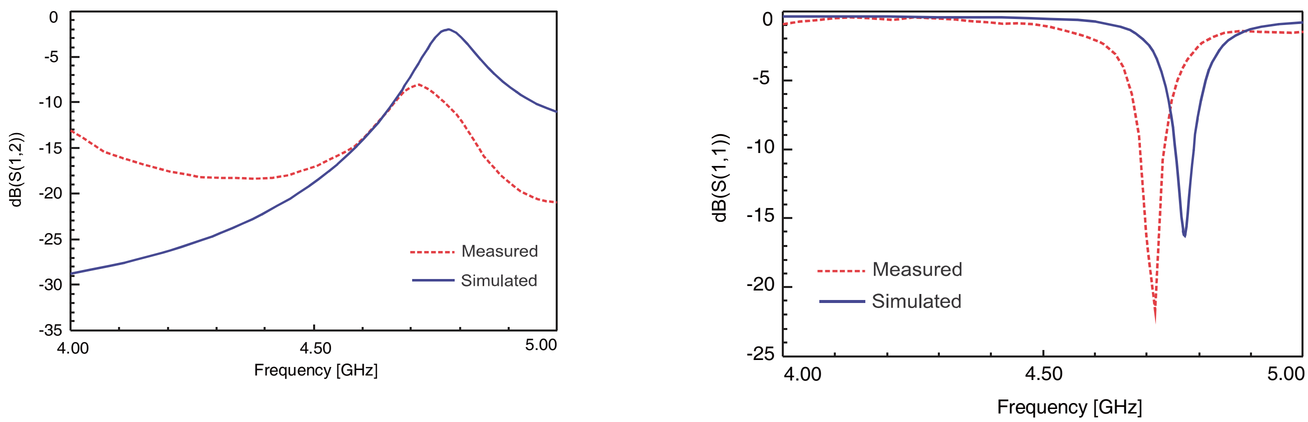
Figure 7. Photograph of the layout of the proposed filter. (a) Top view: Top layer and (b) the middle and ground layer.

Fig. 6 shows the parameters of width and length of the simulation result measured by S_{11} and S_{12} of the TM_{110} circular cavity at 4.75 GHz and has demonstrated that S_{11} is lower than −16.26 dB and S_{12} around −1.2 dB with loaded Q-factor of 47.5. The design of a bandpass filter based on SIWCC was fabricated and tested using Printed Circuit Board technology process with the thickness of the copper clad being 0.018 mm and fabricated using a Rogers RO4350B^{TM}substrate with dielectric constant 3.48 and thickness 1.52 mm. The SIWCC filter is excited by the microstrip line coupled through a triangle probe at the middle layer of the substrate.

Table 3. Comparison between the measurement and simulation results.

Parameter	f_r (GHz)	S_{12} (dB)	S_{11} (dB)
Simulation	4.75	1.2	16.26
Measurement	4.68	6.8	21.0

Photographs of the layout are given in Fig. 7. The overall dimension of the fabricated filter is $60 \times 40\,\text{mm}^2$. The fabricated bandpass filter was tested using a network analyser. For validation purposes, the measurement results were compared with those of the Ansoft HFSS software and shown in Fig. 8 and Table 3. The measured resonant frequency is 4.68 GHz, and the loaded Q-factor is approximately 46.8. Furthermore, the measured return loss and insertion loss are 21.0 dB and 6.8 dB, respectively.



(a) (b)

Figure 8. Comparison between simulation and measurement result (a) Insertion loss, S_{12}. (b) Return loss, S_{11}.

The higher measured insertion loss is mainly due to the imperfect bonding between substrate layers, mismatches in the rectangular window size, and improper alignment during the assembly process. In realization, layers were embedded tightly together to form the desired multilayer structure with an air gap as shown in Fig. 7(b). However, further investigations on the fabrication process are needed to improve the performance of the filter for single and multiple-mode filter based on substrate integrated circular cavity using Low Temperature Co-fired Ceramics (LTCC) [17]. This method is seen as a good solution for compact size filters and to improve the insertion loss. Table 4 compares the performance of the proposed filter with other filters studied in the literature. Among those filters, this work provides better return loss performance and a good narrow bandwidth.

Table 4. Performance comparison of designed filter with other published works.

References	This work	Ref. [18]	Ref. [19]	Ref. [20]
f_r	4.75 GHz	4.0 GHz	2.3 GHz	2.45 GHz
S_{12}	>1.2 dB	>1.0 dB	0.35	>1.0 dB
S_{11}	>21 dB	<10 dB	>13.5 dB	<10 dB
Fractional Bandwidth, BW	100 MHz	83.54 MHz	80.48%	100 MHz
Electrical Size	$60 \times 40\,\text{mm}^2$	$65 \times 40.9\,\text{mm}^2$	$0.12 \times 0.22\ \lambda_g$	$28.4 \times 12.3\,\text{mm}^2$

4. CONCLUSION

This study introduced a new design for a compact double-layer bandpass filter based on SIWCC and TL. A prototype SIWCC bandpass filter was designed and fabricated to operate in TM_{110} mode at 4.75 GHz with 100 MHz fractional bandwidth, which can be applied in satellite and wireless communication systems. Slight discrepancies between measured and simulated values of the frequency shift and insertion loss were observed. In terms of the fabrication process, better bonding techniques are required to be implemented to avoid losses and achieve the desired performance. The overall design was simulated and then verified by experiments to ensure the validity of the concept.

ACKNOWLEDGMENT

The authors would gratefully acknowledge Universiti Teknologi MARA (UiTM) for the financial support of this work.

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