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Corrugated SIW Based Bandpass Filter for Microwave Interferometer and ISM Band Application

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Abstract—A corrugated substrate integrated waveguide (CSIW) based bandpass filter is designed and developed for the microwave interferometer (7.0 GHz) and ISM band (5.7 GHz–5.9 GHz) application. CSIW structure provides a cost-effective solution counter to substrate integrated waveguide (SIW). Initially, the CSIW structure is designed from the design methodology of SIW. Vias are replaced with a quarter wavelength open stub. A metallic inductive post is used for the realization of the bandpass filter from the CSIW structure. Computer simulation technology (CST) software is used for design and simulation of the proposed model. Two structures are implemented for the microwave interferometer and ISM band frequency application. The first structure resonates at the center frequency of 7.023 GHz with the fractional bandwidth of 5.26%. It provides an insertion loss value of less than 1.5 dB and a return loss better than 14 dB. Similarly, the second structure provides passband frequency, from 5.6 GHz to 6.0 GHz, with the insertion loss value less than 1.5 dB and return loss better than 18 dB at the center frequency. It can be used for the ISM band frequency application. The frequency tuning approach is also shown to change the resonance frequency for different applications. For the proof of concept, the proposed filter is fabricated and tested. The measured results are quite similar to the simulation results.

1. INTRODUCTION

Microwave filters have been developed recently based on several methods and techniques, such as microstrip line [1], conventional waveguide technology [2], photonic band gap structure [1], metamaterial structure [3], and substrate integrated waveguide (SIW) technology [4].

Various SIW based active and passive components are proposed by different researchers [5–7]. SIW is the planar form of a waveguide structure realized by embedding metallic vias in a dielectric substrate. It combines advantages of both the conventional metallic waveguide and microstrip line. SIW structure offers a smaller size, lower weight, easy manufacturing than a metallic waveguide, and better power handling and losses than a microstrip line [6]. A bandpass filter using SIW with corrugated waveguide concept is given in [7].

SIW structure with a corrugated wall allows the component development without the conducting vias between the top and bottom planes. It is called a corrugated substrate integrated waveguide (CSIW) [8]. With corrugation, it is possible to achieve the TE_{10} type of boundary condition at the sidewall [9]. In a CSIW structure, vias of SIW structure are replaced with a quarter wavelength microstrip stub [10–12]. It is arranged in a corrugated pattern at the side edge of the wall. The fabrication cost and complexity of CSIW are less than the SIW as it eliminates the vias in the fabrication process

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CSIW design process, from its equivalent SIW structure, is given in [11]. A CSIW based H plane horn antenna for the wideband frequency response (5.3 GHz to 19 GHz) is proposed by Zhao [13]. Mode analysis in the CSIW structure is carried out in [14]. Half mode buried substrate integrated waveguide is presented in [15]. To obtain a wall combination of corrugation, slot and vias are used. It provides low stub input impedance. A CSIW based distributed amplifier is proposed in [10] for the DC isolation between the top and bottom planes. A leaky-wave antenna at 4.5 GHz with a CSIW structure is presented in [9]. It is used for a beam scanning application at a fixed frequency of operation. A tunable bandpass filter using liquid crystal CSIW is given in [16]. A wideband bandpass filter in the frequency range of 12 GHz to 18 GHz with a periodic structure in the CSIW structure is shown in [17].

A bandpass filter is required for a phased lock loop (PLL) system proposed by the authors in [18] for 7.0 GHz center frequency and the radar system development (5.725 GHz–5.875 GHz) at ISM band frequency. The objective of the research work is to realize a bandpass filter for the C band application. Initially, the filter is developed for the microwave interferometer at 7 GHz frequency using a CSIW structure, and same design procedure is used for the design of a bandpass filter for ISM band frequency. The two designs have different applications; however, the design procedures are the same.

Figure 1 shows the SIW structure with its equivalent CSIW structure. It indicates that periodic vias of the SIW structure are replaced by the quarter-wavelength stub (l). The diameter (d) of vias in SIW and stub width (d) in CSIW should be the same. Here, p indicates the pitch between stubs or vias. The width of SIW and CSIW is characterized by a.

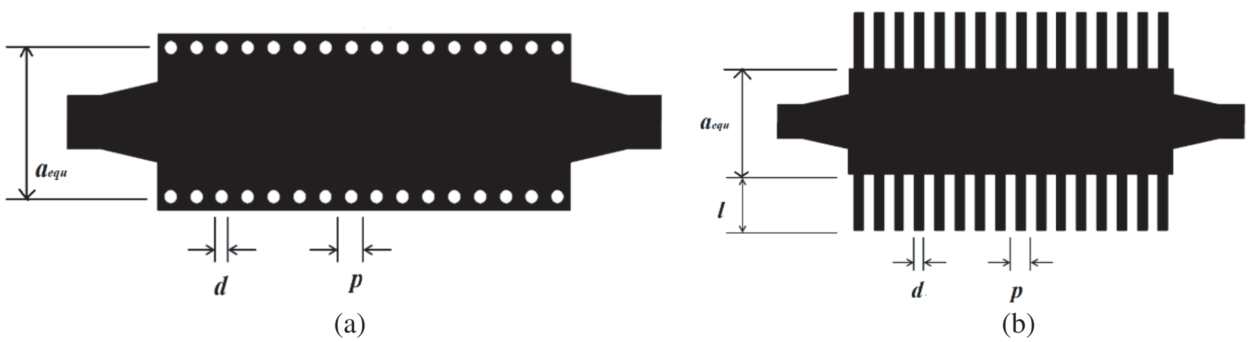

Figure 1. (a) SIW structure. (b) Equivalent CSIW structure.

2. CORRUGATE SUBSTRATE INTEGRATED WAVEGUIDE DESIGN

The design procedure of the CSIW is the same as the design of the SIW structure. The cut-off frequency of the structure can be decided by the width of the waveguide, as given in Equation (1).

$$f_c = \frac{c}{2a_{equ}\sqrt{\varepsilon_r}} \tag{1}$$

Here f_c is the cut-off frequency, c the speed of light in a vacuum ($3 \times 10^8\,\mathrm{ms}^{-1}$), ε_r the relative permittivity, and a_{equ} a width of the waveguide.

The width (d) of the corrugation slot and the pitch (p) between them can be decided similar to the SIW theory. Their equations are given in Equations (2) and (3). The length (l) of the slot is the quarter wavelength at the solution frequency

$$\frac{d}{\lambda_0} \leq 0.1 \tag{2}$$

$$\frac{d}{p} \geq 0.5 \tag{3}$$

Based on the above theory, the CSIW structure is designed at the solution frequency of 5.5 GHz. RT Duroid 5880 is used as a substrate material. Its dimension is tabulated in Table 1.

Table 1. Design parameter of the CSIW.

Parameters	f_c (GHz)	d (mm)	a_{equ} (mm)	p (mm)	ε_r	l (mm)
Value	5.5	1.4	20.22	2.0	2.2	10.19

Figure 2 shows the design of the CSIW at the cut-off frequency of the 5.5 GHz and its electric field distribution. CST software is used for the simulation. A taper type feeding is used for the excitation of the structure.

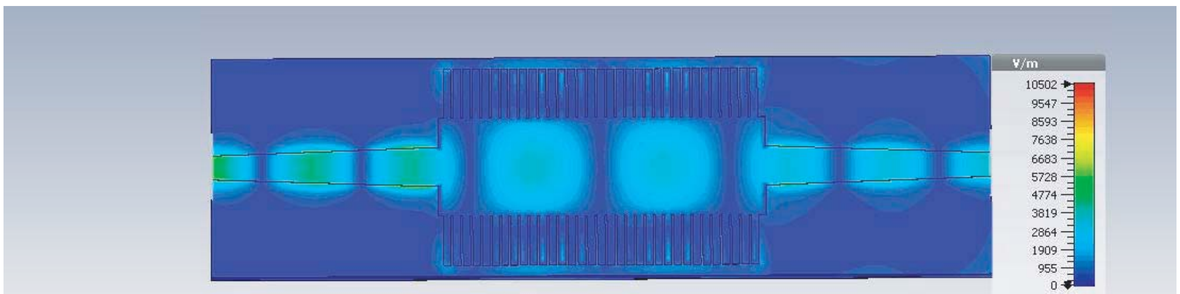

Figure 2. Simulation design of the CSIW using CST.

Simulation results for the S parameter of CSIW are shown in Figure 3. It provides the passband in the frequency range from 5.4 GHz to 8.0 GHz. The insertion loss value in the frequency of interest is less than 1.0 dB, and return loss is better than 15 dB.

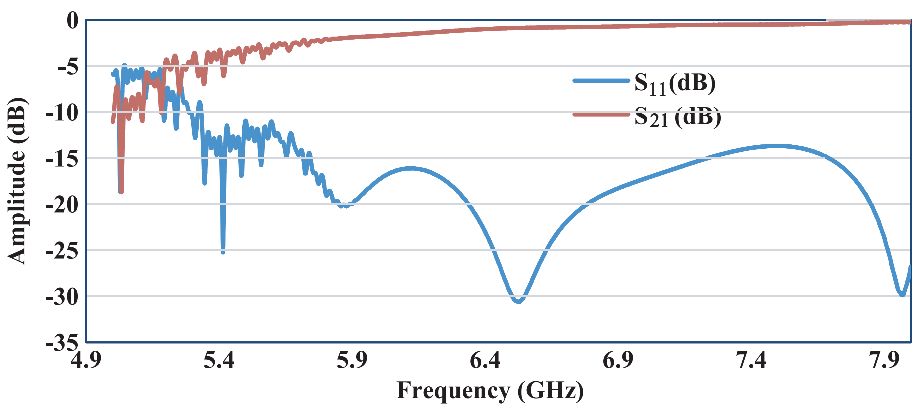

Figure 3. Simulated S parameter result of CSIW.

3. REALIZATION OF THE BANDPASS FILTER FOR MICROWAVE INTERFEROMETER

BPF is required for the center frequency of 7.0 GHz in the PLL system of the interferometer. To realize the structure of CSIW as a bandpass filter concept of post/iris is used. The idea of the iris is generally used in the conventional waveguide. According to the theory, if post/iris is inserted into the waveguide, it will act as a series inductor and shunt capacitor subject to the penetration of the post. If the penetration of the post/iris is such that it touches the top and bottom planes, then it will act as a shunt capacitor. Similarly, if it does not touch the top and bottom plane, it will serve as a series inductor.

Based on the above concept, four metallic posts are inserted into the CSIW structure, as shown in Figure 4. All four posts are penetrated from the top to the bottom planes. The lateral distance between the posts is kept at a one guided wavelength. The incident energy will be reflected between these posts and resonates at a particular frequency.

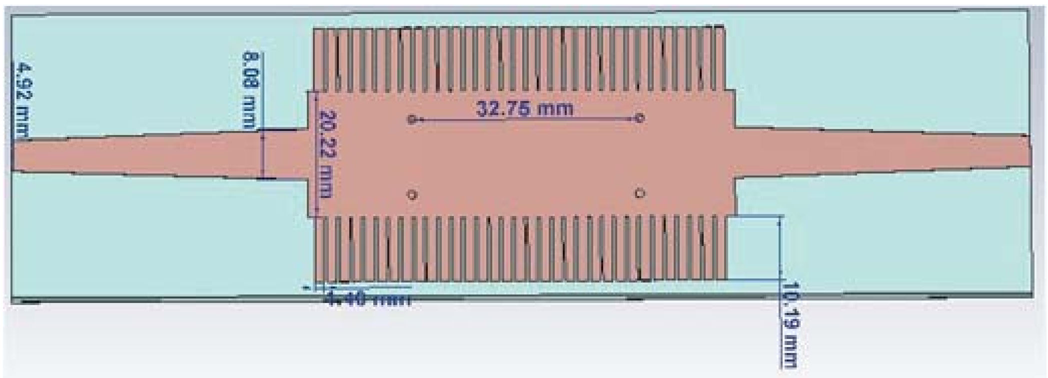

Figure 4. Designed bandpass filter using CSIW.

An equivalent LC circuit of the proposed structure is shown in Figure 5. Here LE is the equivalent inductor because of the top plane; CE is the capacitance between the top plane and bottom plane; $LSTUB$ and $CSTUB$ are the series inductor and capacitor because of the quarter length open stub; $CPOST$ is the equivalent shunt capacitor because of the post inserted between the top plane and bottom plane; $LPOST$ is the equivalent inductance generated because of the metallic posts; CP is the capacitance between the metallic post. S parameter response of the LC circuit simulated in advanced design software (ADS) is shown in Figure 6. It shows that the design provides bandpass response.

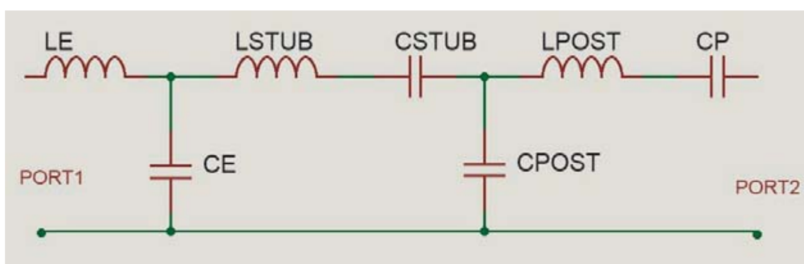

Figure 5. Equivalent LC circuit of the proposed bandpass filter.

The designed bandpass filter is simulated by CST software. The scattering parameter result for the same is shown in Figure 7. It offers a bandpass response from the frequency range of 6.838 GHz ($f1$) to 7.208 GHz ($f2$) with the insertion loss value near 1 dB, and return loss is better than 14 dB. The fractional bandwidth is 5.26% at the center frequency of 7.023 GHz.

$$FBW = \frac{f2 - f1}{f_0} = \frac{7.208 - 6.838}{7.023} = 5.26\% \tag{4}$$

4. FREQUENCY TUNING FOR C BAND APPLICATION

It is possible to tune the resonance frequency to cover various application bands across the C band. Here, two methods are demonstrated for the tuning of the frequency. The first one is by changing the distance between the posts. Diameter of the post is changed in the second method to tune the frequency.

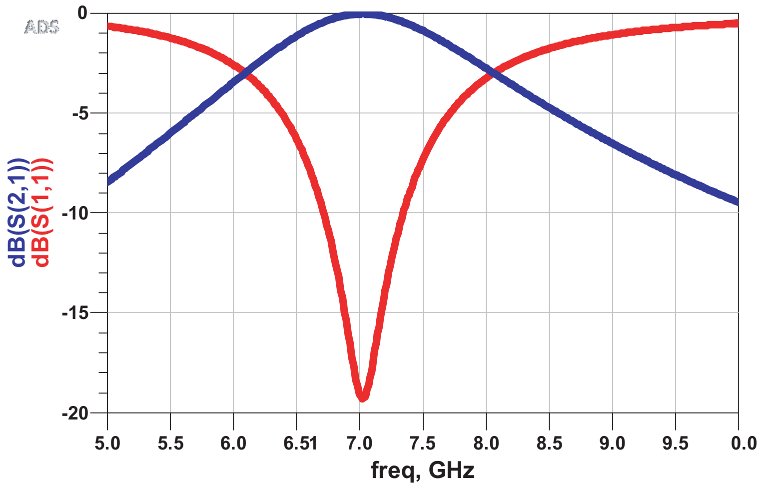

Figure 6. Scattered parameter response of the LC circuit.

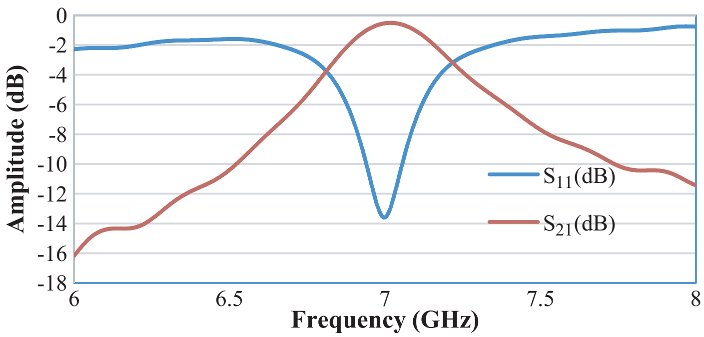

Figure 7. Scattered parameter response of the proposed bandpass filter.

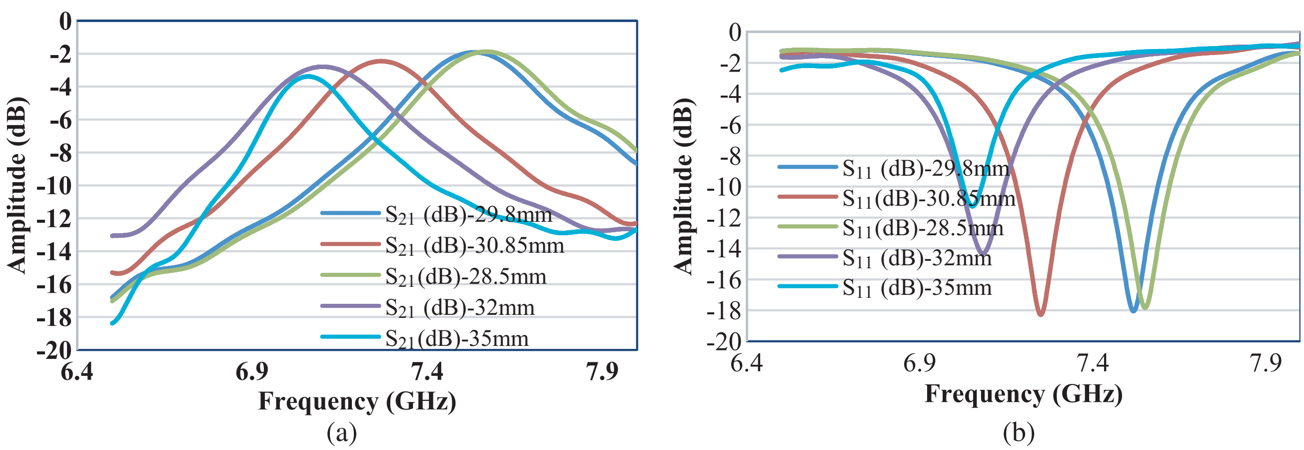

Figure 8. (a) Transmission coefficient. (b) Reflection coefficient result for the various distance between the posts.

Figure 8 shows the transmission coefficient and reflection coefficient results of the proposed structure as a function of the lateral distance between the posts. To understand the frequency tuning concept consider the equivalent electrical circuit shown in Figure 5. Initially, the distance between the posts is kept at a one guided wavelength (32.5 mm). Here, the distance between the posts varies from 29.5 mm to

35 mm, which leads to change in the equivalent shunt capacitance CPOST. It will change the resonance frequency response of the structure. It is verified with the use of ADS software for equivalent LC circuit. Simulation is carried out for the lateral distance between the metallic posts, ranging from 29.8 mm to 35 mm in CST. It is possible to tune the frequency from 6.976 GHz to 7.720 GHz with this possible combination. The achieved bandwidth is from 202 MHz to 319 MHz with insertion loss values ranging from 1.89 dB to 3.42 dB and return loss values from 11.23 dB to 17.78 dB. The numerical data of Figure 8 are tabulated in Table 2.

Table 2. Numerical data of Figure 8.

Distance between the posts	Passband frequency (GHz)	Insertion loss (dB)	Return loss (dB)	Band-width (MHz)
28.5 mm	7.436 to 7.720	1.89	17.78	284
29.8 mm	7.371 to 7.609	1.97	18.05	319
30.8 mm	7.137 to 7.401	2.45	18.29	264
32.0 mm	6.992 to 7.245	2.81	14.32	254
35.0 mm	6.976 to 7.178	3.42	11.23	202

From Figure 8 and Table 2, it is shown that by reducing the distance between the posts (corresponding to change in the guided wavelength value), the resonance frequency is shifted to higher band as well as reduces the insertion loss and increases the return loss value.

Figure 9 shows the simulation result of the transmission coefficient and reflection coefficient for different diameters of the posts. The diameter of the post is varied from 0.1 mm to 0.5 mm. The corresponding result indicates possible frequency tuning from 6.929 GHz to 7.292 GHz with bandwidth variation from 133 MHz to 242 MHz. The numerical data of Figure 10 are tabulated in Table 3.

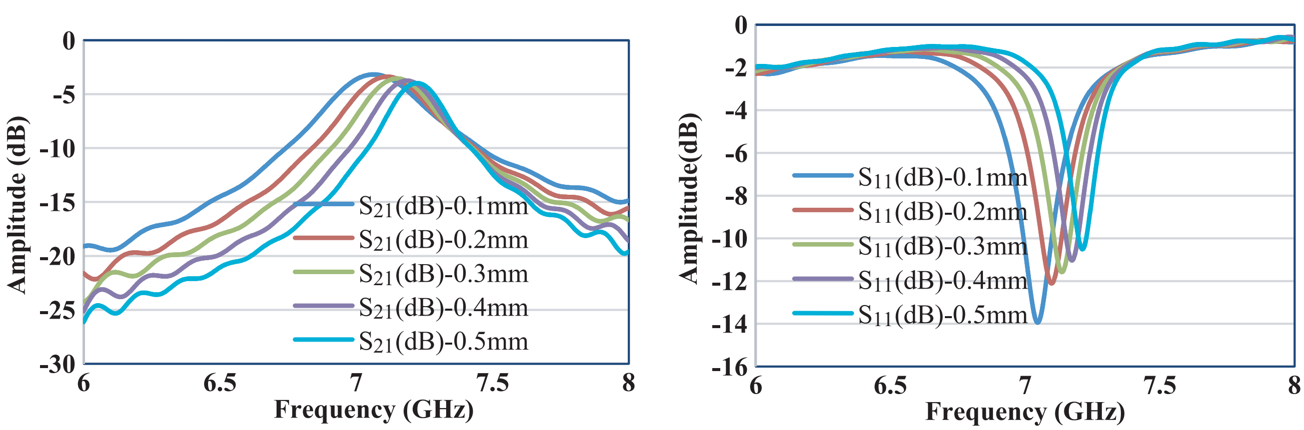

Figure 9. Transmission & Reflection coefficient result for the various diameter of the post.

From the numerical data of Figure 9 and Table 2, it can be concluded that lower diameter of the post provides better insertion and return loss values with higher bandwidth than higher diameter.

5. REALIZATION OF THE BANDPASS FILTER FOR ISM BAND APPLICATION

As discussed in the introduction section, the second objective is to design a bandpass filter for the ISM band (5.7 GHz–5.9 GHz) frequency. The concept discussed in Section 3 and Section 4 is utilized here to realize the bandpass filter. For this, firstly a CSIW based structure is intended for the cut-off frequency

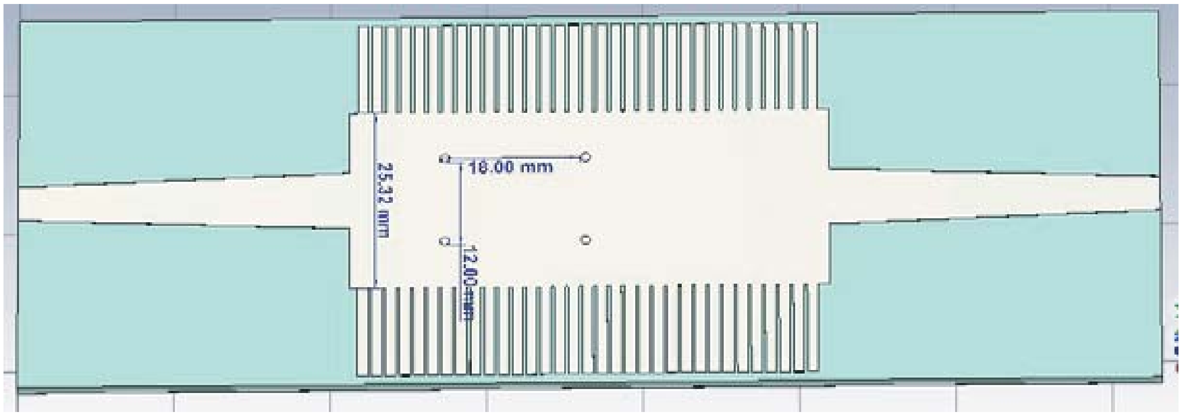

Figure 10. Designed bandpass filter for 5.6 GHz–6.0 GHz passband.

Table 3. Numerical data of Figure 9.

Diameter of post	**Passband frequency (GHz)**	**Insertion loss (dB)**	**Return loss (dB)**	**Bandwidth (MHz)**
0.1 mm	6.929 to 7.171	3.51	13.91	242
0.2 mm	6.998 to 7.239	3.64	12.10	241
0.3 mm	7.052 to 7.271	3.96	11.57	219
0.4 mm	7.116 to 7.276	3.99	11.03	160
0.5 mm	7.159 to 7.292	4.11	10.48	133

Table 4. Design parameter of the CSIW for 4 GHz cut-off frequency.

Parameters	f_c (GHz)	d (mm)	a_{equ} (mm)	p (mm)	ε_r	l (mm)
Value	4.0	1.4	25.32	2.0	2.2	12.64

of 4 GHz with RT Duroid 5880 used as a substrate material. The design parameters of basic CSIW with its value are shown in Table 4. Then, metallic capacitive posts are used to realize the bandpass filter. The designed bandpass filter with the insertion of the metallic post is shown in Figure 10. The corresponding simulated S parameter result is shown in Figure 11. It provides a bandpass response from the frequency range 5.6 GHz to 6.0 GHz. The value of insertion loss is less than 1 dB, and return loss is 18 dB at a center frequency of 5.8 GHz.

6. PROTOTYPE REALIZATION

The designed bandpass filter is fabricated for the prototype realization. The fabricated bandpass filter for 5.6 GHz to 6.0 GHz of passband frequency is shown in Figure 12. A filter is also developed for an interferometer system.

The S-parameters of the filters have been measured using a vector network analyzer. The measured S-parameters of both the filters are given in Figure 13 along with their simulation results. They are quite similar to the simulated ones with the minor change in the frequency response because of the fabrication tolerance.

The proposed filters are compared with the previously published work of filters using SIW and

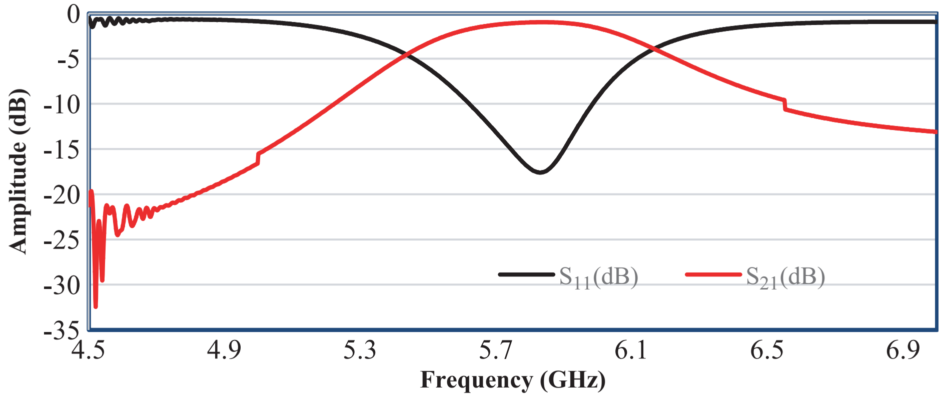

Figure 11. Simulated S parameters of the proposed structure.

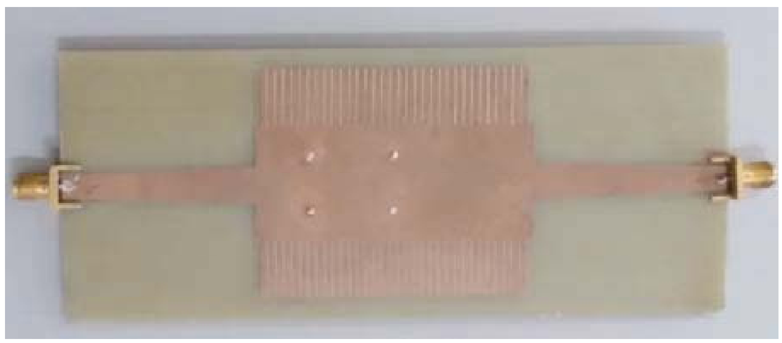

Figure 12. Developed bandpass filter for prototype realization.

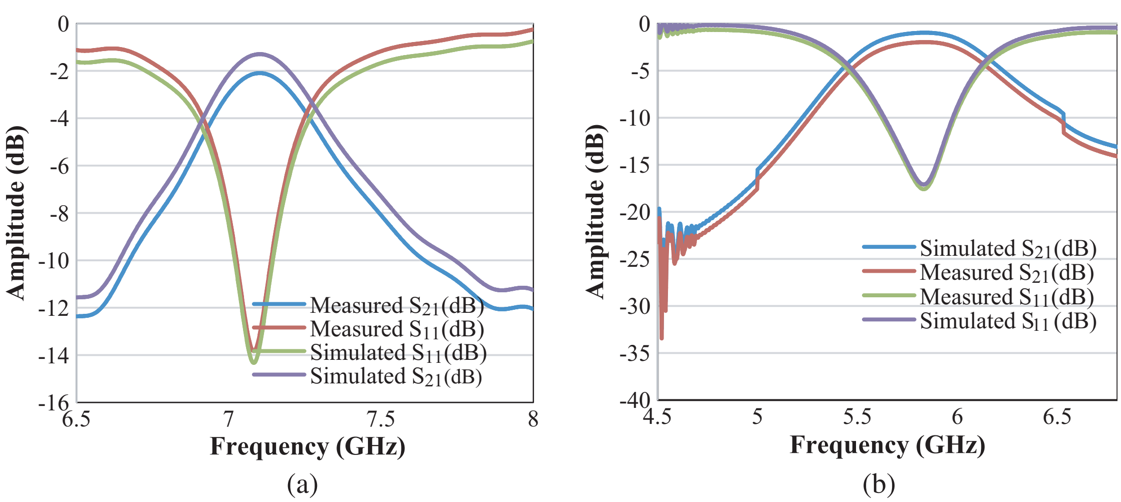

Figure 13. Measured frequency response of bandpass filter for (a) interferometer, (b) ISM band application.

CSIW technology. A comparison table is tabulated in Table 5. They provide less fabrication cost and complexity than [19, 20] and less insertion loss than [16]. The fabrication cost is low because the rows of metallic vias (platted through hole) are replaced with the quarter wave open stub. It leads to a single layer design with the constant ground plane.

Table 5. Comparison of the proposed filter with previously published work.

Ref.	Passband (GHz)	Types of structure	Insertion loss (dB)	Return loss (dB)	Fabrication cost
[19]	6.56–7.4	SIW	~ 1.5	> 10	High
[20]	5.79–5.96	SIW	~ 1.5	> 10	High
[16]	10.15–10.45	SICW	~ 2.4	> 10	-
[17]	11.52–18.71	CSIW	~ 1.9	> 10	-
Proposed	5.6–6.0	CSIW	~ 1.5	> 10	Low
Proposed	6.83–7.20	CSIW	~ 2.0	> 10	Low

7. CONCLUSION

In this article, a CSIW based BPF has been designed and developed in for microwave interferometer (6.8 GHz to 7.2 GHz) and ISM band (5.725 GHz–5.875 GHz) application. Initially, the CSIW structure is designed from its equivalent SIW structure. The concept of a metallic post is used for the design of the filter. The proposed structure provides better performance in terms of transmission characteristics. The insertion loss values for both the structures are less than 2 dB, while the return loss is better than 14 dB. The frequency tuning approach is also discussed to develop a BPF according to the user's requirements. The proposed structure is fabricated, and measured results indicate similarity with the simulated ones.

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