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Compact Dual-Band SIW Band Pass Filter Using CSRR and DGS Structure Resonators

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Abstract—In this paper, a Substrate Integrated Waveguide (SIW) band pass filter loaded with a square Complementary Split Ring Resonator (CSRR) etched with Defected Ground Structure (DGS) is proposed. SIW is a promising candidate for the design and development of various microwave and millimeter wave components useful in communication systems. Due to the evanescent mode propagation and TE_{10} mode of the cavity, dual band (5.57/7.84 GHz) filtering is achieved with a 3 dB fractional bandwidth (FBW) of 6.8% and 4.1%, respectively. The dual bands achieve a low insertion loss of 1.8 dB and 2 dB, respectively. Cursor head DGS improves the out of band rejection to a greater level. The configuration is investigated with its corresponding circuit and simulated using Computer Simulation Technology (CST) software. The prototype is fabricated using a Rogers substrate with ε_r of 3.5 and tested. This prototype finds its application in C band satellite communication systems. The measured results are consistent with the simulated ones.

1. INTRODUCTION

In recent times, there has been a great demand for low cost, miniaturized and high performance microwave and millimeter wave components. Substrate Integrated Waveguide (SIW) was reported early in 2003 [1]. The side walls of the metallic waveguide are replaced by rows of metallic posts which guide the electromagnetic waves in Transverse Electric (TE_{mn}) mode. The absence of Transverse Magnetic (TM) modes in the SIW makes it very useful in the filter design. Even though planar transmission lines such as coplanar waveguide fed microwave components were developed [2–5], the high degree of miniaturization was not attained. However, SIW has the advantage of compact size, low cost, light weight, and is of planar in nature. Hence, it is explored in the design and development of various microwave components such as antennas, filters, couplers, and power dividers [6–9].

Complementary Split Ring Resonator (CSRR) was first proposed in 2005 [10]. CSRR exhibits the same resonant frequency as that of its counterpart Split Ring Resonator (SRR). But it behaves as an electric dipole under the influence of axial electric field and provides the negative permittivity [11, 12]. Employing CSRR into an SIW structure leads to the existence of evanescent wave, thus providing a passband well below the cutoff frequency of the waveguide structure.

A compact slot embedded in the bottom plane of a microwave or millimeter wave components is designated as a Defected Ground Structure (DGS), and it was reported in 1999 [13]. It is accomplished by etching periodic or aperiodic patterns either in horizontal or vertical manner on the ground metallic layer. The defects created in the ground plane underneath the signal transmission line interrupt the distribution of current. Because of this, the transmission line characteristics are changed by the addition of slot inductance and slot capacitance thus in turn creating an extra transmission zero. On employing DGS in the filter development, selectivity can be improved to a greater extent.

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Dual band filters are very essential in communication applications. Dual band response can be achieved by different techniques. Generally, it is attained with a multi-path circuit produced by degenerate modes [14]. In [15], a triple corner cut SIW cavity dual band filter is realized by means of dual modes. The destructive termination of these modes produces a transmission zero. SIW resonator operating in TE_{100} and TE_{201} modes evolving from SIW-transmission-line structure is explored in [16]. Dual bands are also achieved by etching E-shaped slots on the edges of SIW cavities [17] and also by using quadruple folded SIWs [18]. A dual wideband SIW filter, one band in S band and the other in C band, was developed [19]. Also, SIW filters with dumbbell-shaped DGS showing dual wideband responses are demonstrated in [20]. However, narrow dual-band filters are in great demand. We intend to develop a twin band SIW filter with narrow band responses.

To achieve a miniaturized filter, all the three structures, i.e., SIW, CSRR, and DGS, are blended, and a novel dual and narrow band pass filter is proposed in this work. To validate the concept, a dual-band (5.57/7.84 GHz) band pass filter is developed using Rogers RO4003C Lopro ($\varepsilon_r = 3.5$, $\tan\delta = 0.0027$) with a substrate height (h) of 0.508 mm. The proposed filter achieves superior selectivity, little insertion loss, eminent inter band isolation, and miniaturized size.

2. PROPOSED CONFIGURATION AND WORKING PRINCIPLE

2.1. Design of Stage 1

SIW consists of three layers, i.e., top metallic layer, substrate layer, and a bottom metallic ground plane. It incorporates two rows of metallic posts on both sides of the substrate as shown in Figure 1.

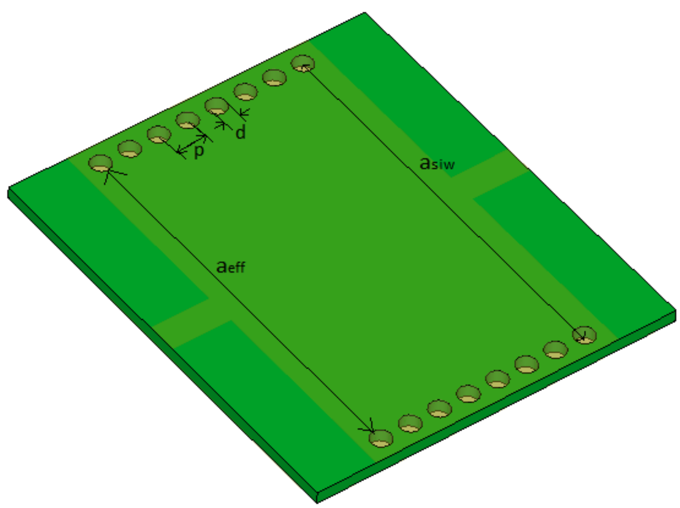


Figure 1. Perspective view of SIW.

For a SIW cavity, the resonant frequency, f_c, for TE_{10} mode is given as [21]

$$f_c = \frac{c}{2a_{\mathit{eff}}\sqrt{\varepsilon_r}} \quad (1)$$

where c is the light velocity in air, a_{eff} the effective dielectric width of the waveguide, and ε_r the substrate permittivity .

The effective dielectric width of the waveguide is related to the SIW width as [22],

$$a_{\mathit{eff}} = a_{SIW} - \frac{d^2}{0.95 * p} \quad (2)$$

where a_{SIW} is the SIW width, d the via diameter, and p the pitch between the vias. To minimize the radiation leakage through the vias, d and p should be selected such that they satisfy the criteria

$p \leq 2d$ and $0.5p \leq d \leq 0.1\lambda_0$ (λ_0 is the free space wavelength at the first resonant frequency). The characteristic impedance of SIW has been explored in [23].

Based on Equations (1) and (2), a SIW structure with a cutoff frequency of 5.75 GHz is designed, and it is excited by a 50 Ω microstrip feed. It exhibits a high pass characteristic at the designed resonant frequency. The SIW structure along with the feed is depicted in Figure 2.

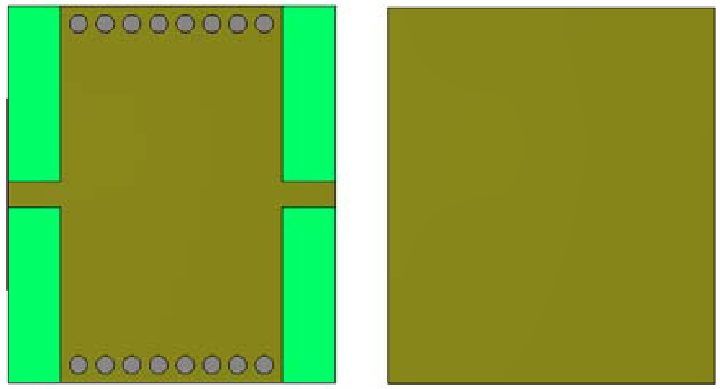


Figure 2. Top and bottom view of the SIW structure with microstrip feed.

2.2. Design of Stage 2

The physical geometry of a CSRR is exposed in Figure 3(a). When being incorporated in SIW, CSRR provides passband well below the resonant frequency of the SIW structure [24]. It consists of two square metallic resonant rings with a split on opposite sides. 'l_o' is the outer ring length, 'l_i' the inner ring length, 'g' the split gap, 's' the ring width, and 'r' the spacing between the two rings. While operating in the resonant frequency, CSRR operates as an electric dipole under the influence of electric field in vertical direction. As a result, it is capable of being operated as a shunt connected inductor and capacitor circuit (LC) as shown in Figure 3(b). L_r and C_r denote the mutual inductance and self capacitance of the two rings, respectively. They are calculated as in [10],

$$L_r = (4l_o - g)\,L_{out} + (4l_i - g)\,L_{in} \tag{3}$$

$$C_r = (4l_o - g)\,C_{out} + (4l_i - g)\,C_{in} \tag{4}$$

where L_{out} and C_{out} are the unit characteristic inductance and capacitance of the outer ring, and L_{in} and C_{in} are the unit characteristic inductance and capacitance of the inner ring. The resonant frequency of the CSRR is demonstrated as,

$$f_{CSRR} = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{5}$$

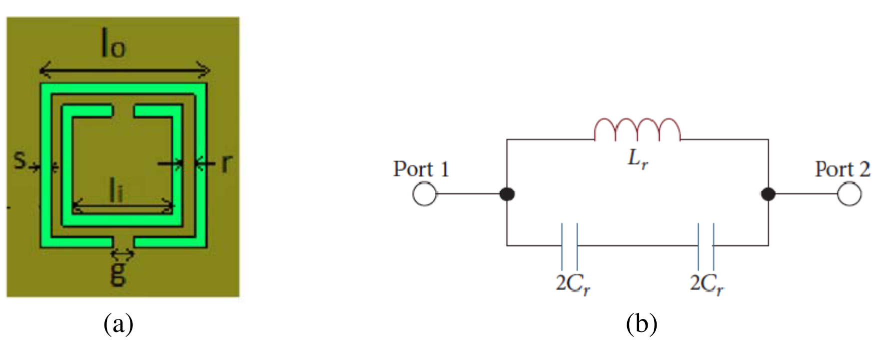


Figure 3. (a) CSRR — Physical structure. (b) CSRR — Equivalent structure.

With using Equations (3)–(5), a square CSRR with a resonant frequency of 5.57 GHz is designed, and it is etched on the bottom plane of the SIW structure as depicted in Figure 4. This design provides dual bands in which the second passband does not have a sharp out of band rejection.

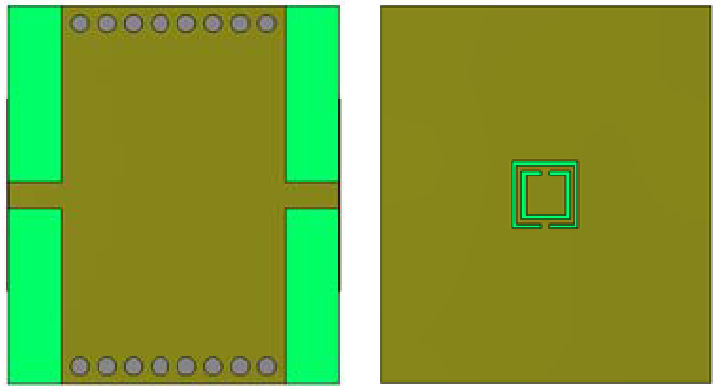


Figure 4. Top and bottom view of SIW structure loaded with CSRR.

2.3. Design of Stage 3

In order to achieve good out of band rejection at the second passband, DGS can be etched on the bottom plane. DGS could be either element cell or multiple cells arranged periodically. Various DGS structures, such as dumbbell, cursor head slot, and H-shape slots, are used in practice. Any geometrical slot etched on the ground plane disturbs the current distribution, and thus it changes the characteristic impedance of the transmission line [25]. In this proposed design, we have etched periodic cursor head DGS operating at 10.5 GHz one on either side of the square CSRR at a distance 'G' in order to improve the selectivity by providing a steep rejection outside the band. Cursor head defect structure is shown in Figure 5(a), and its equivalent circuit is revealed in Figure 5(b). 'L_1' is the slot length, 'W_1' the slot width, and 'L_2' the cursor length. The circuit elements C_c and L_c can be found as in [26]

$$C_c = \frac{5 f_c}{\pi (f_o^2 - f_c^2)} \tag{6}$$

$$L_c = \frac{250}{\pi^2 f_o^2 C_c} \tag{7}$$

where the cutoff frequency and stopband resonant frequency are specified as f_c and f_o, respectively.

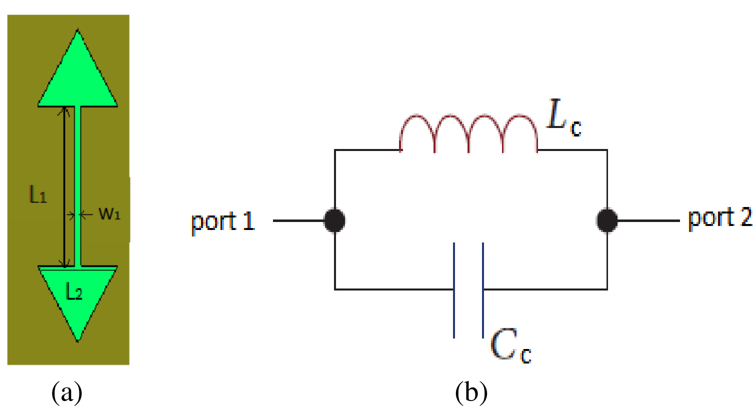


Figure 5. (a) Cursor head DGS structure. (b) Its equivalent circuit.

The geometrical views of the projected filter are shown in Figure 6, and its parameters are tabulated in Table 1.

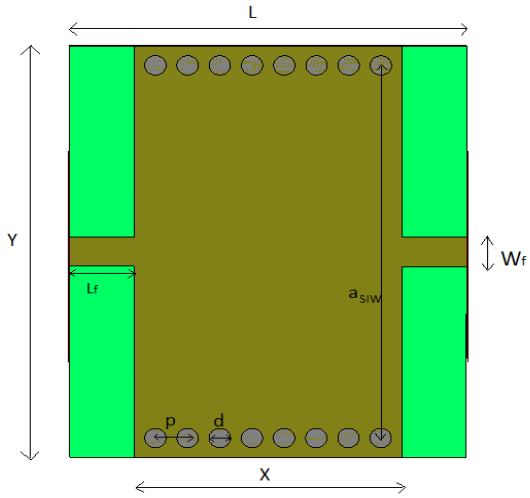


Figure 6. Top and bottom view of the proposed SIW BPF loaded with CSRR and DGS.

Table 1. Dimensions of the proposed SIW dual band filter.

Parameters	X	Y	L	L_f	W_f	p	d	a_{siw}	L_1	L_2	W_1	G	r	l_o	l_i	s	g
Values (mm)	10	17	14.8	0.8	1.2	1.2	0.8	14.5	4.5	2.5	0.2	2	0.2	3	1.8	0.2	0.4

3. PARAMETRIC ANALYSIS OF THE PROPOSED FILTER

The parametric study of the proposed filter is done using CST. The parameters of the cursor head DGS have been varied, and study has been performed in order to determine the optimum values to accomplish a good out of band rejection in the second passband. 'L_1' — the slot length, 'L_2' — the

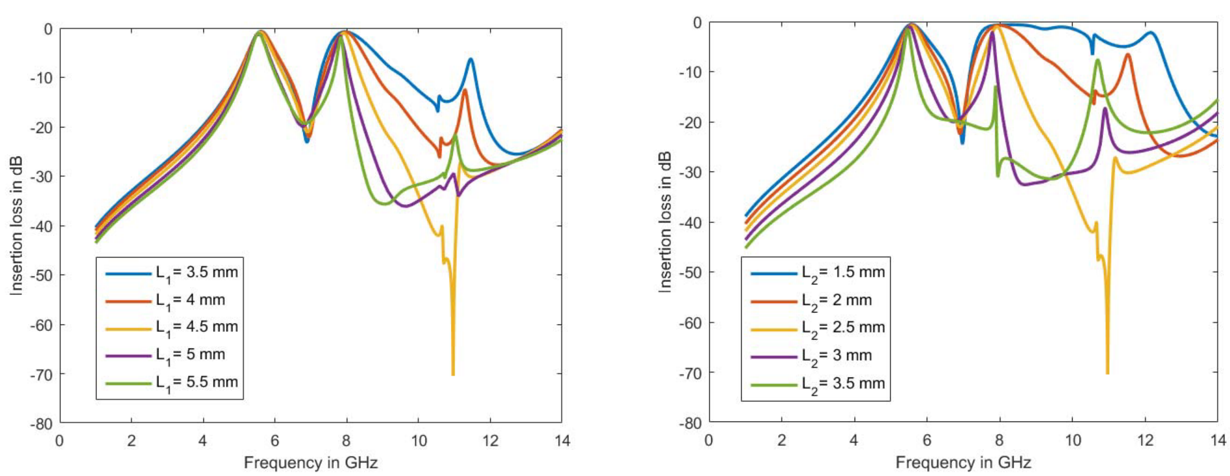
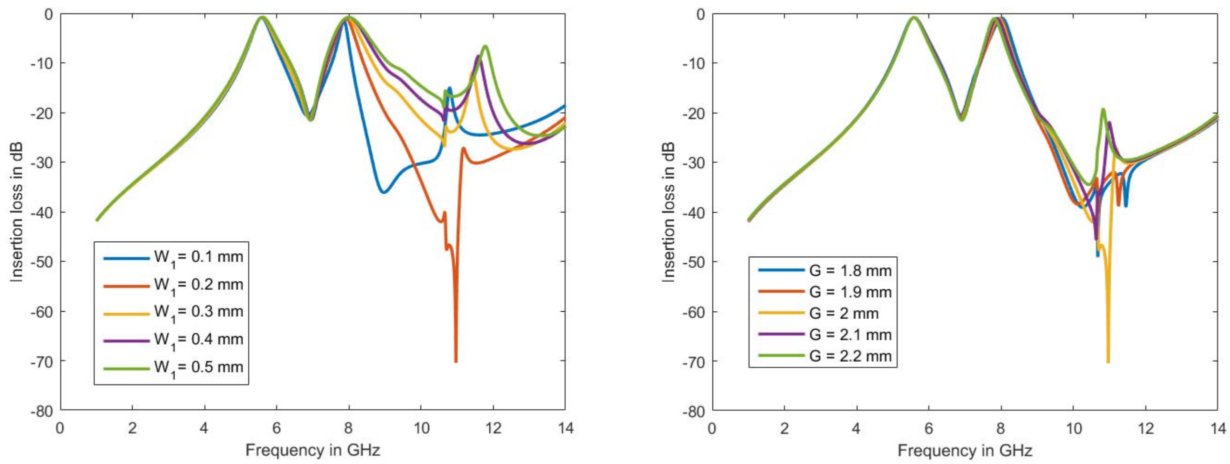


Figure 7. Simulated insertion loss for various (a) L_1 values and (b) L_2 values.



(a) (b)

Figure 8. Simulated insertion loss for various (a) W_1 values and (b) G values.

cursor head length, 'W_1' — the slot width, and 'G' — the gap between the cursor head DGS and the square CSRR which has been varied in steps, and its impact is found as shown in Figures 7 and 8. The increase in L_1 and L_2 improves the out of band rejection whereas the increase in W_1 makes the out of band rejection poorer. The increase in G improves the out of band rejection in the second passband.

It is found that $L1 = 4.5$ mm, $L_2 = 2.5$, $W_1 = 0.2$, $G = 2$ mm are the optimum values. Cursor head DGS etched from the bottom layer will block the signals propagating in the microstrip line at the designed frequency (10.5 GHz) thus providing a transmission zero at 10.5 GHz. Thus, it results in excellent selectivity along with maintaining fine in band characteristics.

4. EXPERIMENTAL VALIDATION

The proposed filter is fabricated using Rogers RO4003C Lopro ($\varepsilon_r = 3.5$, $\tan\delta = 0.0027$) with a substrate height of 0.508 mm. The top and bottom views of the designed prototype are shown in Figure 9. The filter is simulated using CST software, and it is tested using Agilent Vector Network Analyzer.

The SIW structure exhibits a high pass nature with a cutoff frequency of 5.75 GHz as shown in Figure 10(a). The incorporation of Square CSRR on the ground plane generates dual band responses

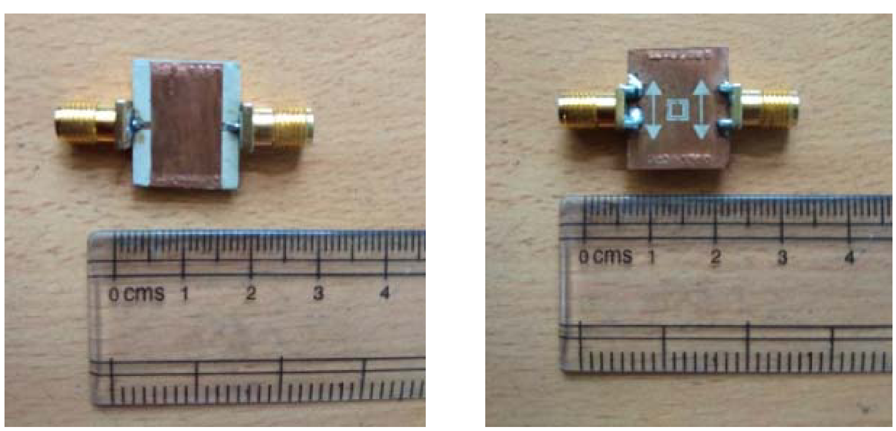


Figure 9. Top and bottom view of the fabricated prototype.

as depicted in Figure 10(b). The first passband is created due to the evanescent mode, and the second pass band is due to TE_{10} resonant mode. The selectivity of the second passband is not superior. Hence, a pair of cursor head DGSs is loaded on the bottom of the SIW structure on either side of the CSRR.

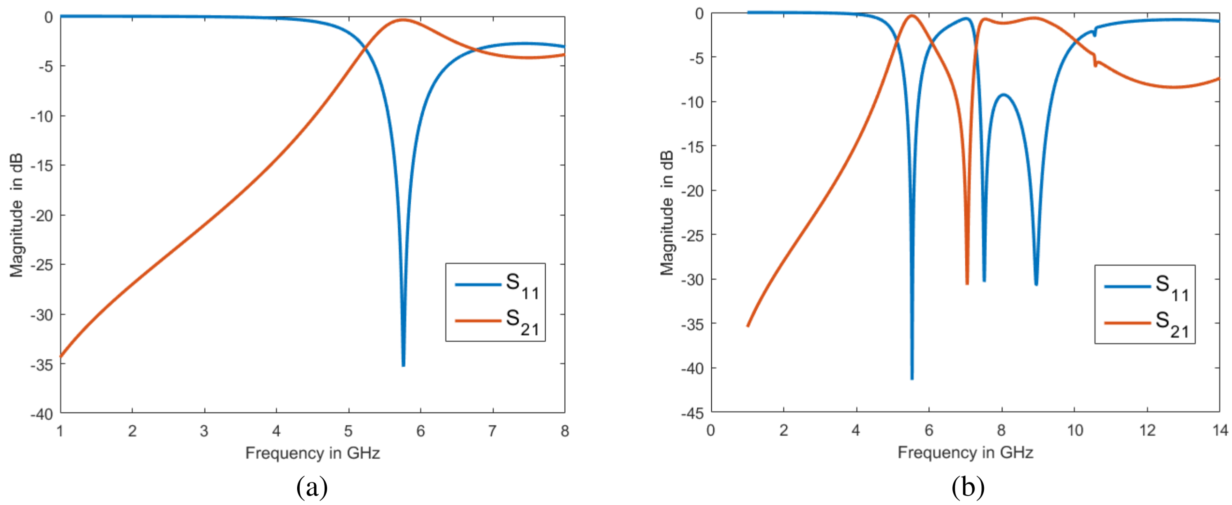


Figure 10. (a) Simulated S-parameters of the SIW structure, (b) simulated S-parameters of the SIW structure loaded with CSRR.

Table 2. Comparison with other available SIW filters.

References	Size	Insertion loss (dB)	f_c of the pass bands (GHz)	3-dB Fractional Bandwidth (%)
[14]	$0.73\lambda_g \times 0.73\lambda_g$	1.8/1.94	5.3/8.7	6.8/3.2
[15]	$2.11\lambda_g \times 2.11\lambda_g$	2.2/2	5.85/6.15	1.3/1.3
[16]	$1.38\lambda_g \times 0.78\lambda_g$	1.2/1.3	4.8/5.4	3.8/3.9
Our work	$0.41\lambda_g \times 0.47\lambda_g$	1.8/2	5.57/7.84	6.8/4.1

λ_g — guided wavelength at the center frequency of the first pass band.

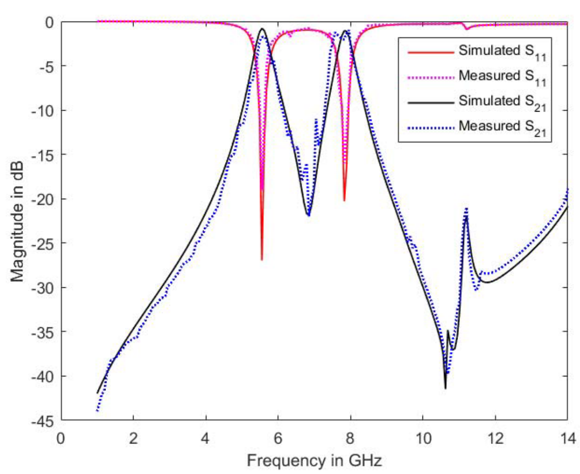


Figure 11. Simulated and measured S-parameters of the proposed SIW band pass filter.

They block the electromagnetic waves on the transmission line at 10.5 GHz and generate a transmission zero, thus improving the selectivity of the second passband. Thus, the proposed SIW band pass filter possesses dual bands at 5.57 GHz and 7.84 GHz with 3 dB fractional bandwidths of 6.8% and 4.1%, respectively. The 5.57 and 7.84 GHz bands exhibit an insertion loss of 1.8 dB and 2 dB, respectively. The proposed narrow band filter possesses low insertion loss, good out of band rejection, and high inter-band isolation. The proposed work is compared with various available SIW filters and tabulated in Table 2.

The simulated and measured return losses and insertion losses of the proposed SIW dual narrow band filter for various frequencies are depicted in Figure 11.

5. CONCLUSION

A novel dual narrow band CSRR loaded SIW band pass filter incorporated with a cursor head DGS is developed for C band satellite communication applications. The first passband is created due to the evanescent mode, and the second pass band is due to TE_{10} resonant mode. The proposed filter is compact with a dimension of $0.41\lambda_g \times 0.47\lambda_g$. Metamaterial is loaded in the SIW as a candidate for obtaining miniaturization. The out of band rejection is improved to a greater extent by etching the DGS on the ground plane. The proposed prototype exhibits dual band operation at 5.57 GHz and 7.84 GHz with insertion loss of 1.8 dB and 2 dB, respectively, compact size, low insertion loss, narrow bandwidth, and high selectivity. The measured results are in good agreement with the simulated ones.

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