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Compact Substrate Integrated Waveguide Multiband Band Pass Filter using Octagonal Complementary Split Ring Resonators

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Abstract

Transmission line structure based on substrate integrated waveguide (SIW) loaded with new structure of octagonal complementary split ring resonator (CSRR) has been proposed. The SIW loaded CSRR pair is used in dual/quad octagonal structure to design dual band pass filter (single and double pole) with improved performance characteristics. The proposed band pass filter (BPF) yields two passbands (3.82-4.39) GHz (566 MHz) and (6.18-6.31) GHz (123MHz) with center frequency at 3.97 GHz and 6.2 GHz respectively. The simulated results are in good agreement with measured result. The results obtained by proposed filter are compared with others as reported in literature. It can be seen that the performance parameters such as bandwidth and insertion loss are improved by 14.27%, 0.7dB in first pass band and 2%, 2 dB in a second pass band respectively with transmission zero 5.57 GHz at stopband. The proposed filter structure leads to chronological minimization in size, low cost and quality factor obtained is 153. The proposed filter can be used in C-band of microwave link and easily integrated with other circuits.

Keywords: Microstrip filters, Complementary Split Ring Resonators (CSRRs), Balanced right/left handed Transmission Lines, Band Pass Filter.

INTRODUCTION

Miniaturized multi-band filters are the essential component of microwave circuit for use in space communication system. Consequently, it has received research interest among scientists and engineers; as a result, significant progress has been made in the design of these filters in the recent years. Nevertheless, it has remained a challenge for having one single filter with compact size and reasonable performance [1]. In the present day scenario special electromagnetic structures like split rings resonators (SRR) and complementary split rings resonators CSRR etc., are used for improving the performance standard of a microwave filter circuit [2]–[6]. CSRRs are the constitutive bricks for the synthesis of negative permittivity and permeability media based on resonant elements. Also from duality, the dominant mechanism for CSRRs excitation is electric coupling. SIW embedded with CSRR structure combines the advantages of planar and voluminous structures, suppressing undesired various harmonics in microwave and millimeter wave circuit along with undesired frequency band [2]. The SRR originally proposed by Pendry et al. having negative permittivity & permeability [7] and has achieved a high quality of interest for designing such filter in microwave range [8]–[10]. The complementary structure of SRR i.e CSRR provides negative effective permittivity near its resonant frequency and hence provides a sharp rejection band [10], [11]. Periodic structures for planner transmission lines with SIW filters have been subjected to intensive studies [12]. The SIW structure allows high-quality factor, improved selectivity with a reduction in size, multiband for wide application in wireless and satellite communication system [13]. Further, special electromagnetic structures like SRR, CSRR have been integrated into the SIW to further improve its performance [12]–[14]. Many dual or triple band filters have been implemented using SRR [15], [16] and subsequently, different CSRR loaded SIW filters had been proposed where in attempts were made to miniaturize the filters, as reported by the authors [12], [17]–[23].

In this paper, a novel single and double pole dual band compact substrate integrated waveguide dual bandpass filter using octagonal complementary split ring resonators. The measured results are in good agreement with simulated result. The results are compared with other as reported in literature. This shows improved performance in terms of bandwidth, insertion loss and quality factor. The proposed compact filter can be C-band link of microwave communication system.

CHARACTERIZATION OF UNIT CELL

The design of the band pass filter circuit incorporates three stages namely SIW, CSRR structure and SIW loaded CSRR. The proposed SIW dual bandpass filter using octagonal CSRR is discussed in detail in following section.

Design procedure of SIW structure

The SIW structure consists of two linear metallic via array which have been designed and modelled into a dielectric substrate with $\varepsilon_r = 2.2$ and height h = $0.004\lambda_g$. They preserve the advantage of waveguide structure such as metallic via confined the electromagnetic fields inside the SIW. The synthesized integrated waveguide is a good compromise between the air filled waveguide and planner circuit [6] shown in Figure 1. The waveguide cutoff frequency is calculated with a width (W) and substrate thickness (h). The W between the two arrays determines the propagation constant.

The design equations of SIW resonator are [12]–[14].

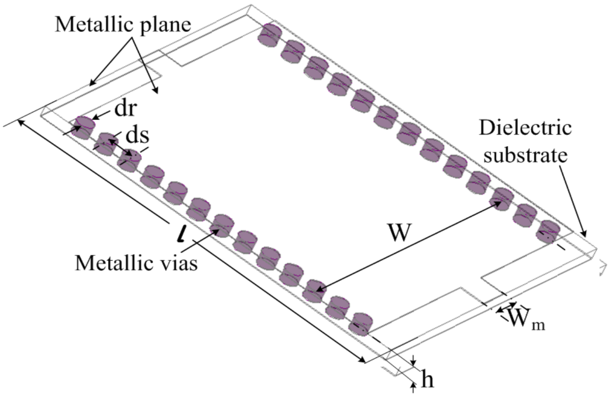


Figure 1: Layout of a typical SIW structure

$$f_0 = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{\frac{1}{W_{eff}^2}+\frac{1}{l_{eff}^2}} \tag{1}$$

Where,

$$W_{eff} = W - 1.08\frac{dr^2}{ds} + 0.1\frac{dr^2}{W} \tag{2}$$

$$l_{eff} = W - 1.08\frac{dr^2}{ds} + 0.1\frac{dr^2}{l} \tag{3}$$

dr is the diameter of the vias, ds is the spacing between them and W is the spacing between the two SIW arrays. The size of the metallised vias have a diameter of 0.8 mm and a center-to-center pitch around 1.2 mm. The parameter return loss and radiation loss are minimized by selecting proper via diameter (dr) and pitch (ds) dimensions. The synthesized waveguide becomes free from leakage loss. For an electrical small post, (dr < 0.016 λ_g) the radiation loss is lower than (0.014dB/ λ_g) with a ratio of dr/ds = 0.67.

Design of CSRR structure

The construction scheme of octagonal CSRR along with an analysis of band pass waveguide filter by using a single CSRR is upgraded by adding a central section in proposed double ring loaded octagonal CSRR as shown in Figure 2. The dimensions of the CSRR are given below: the side of the outer ring a = 2.35mm and slit width d_1= 0.45mm and side of the inner ring b = 1.87mm and slit width d_2 = 0.2mm for design convenience, width of the ring c_1 = c_2 = 0.3mm. Different shape of the resonator is used for reference filter design [2], [12], [15]. The octagonal shape resonator has compact geometry. The dimension of above resonator is obtained by implementing the initial method which is based on dual counterpart (SRRs) consideration [8], [15]. Multiple tuning procedures [19] are used to determine the optimized dimensions of the above octagonal CSRR to obtain the required characteristics and resonance frequency.

The basic octagonal loop resonator consists of eight identical arm sides has been proposed. The resonance frequency of

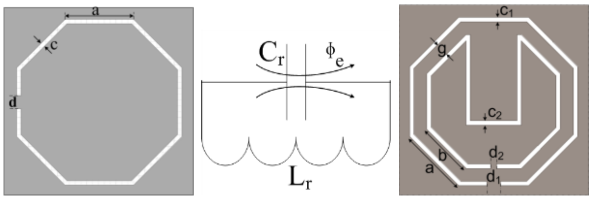


Figure 2: Basic unit CSRR (left), Equivalent circuit (middle), Proposed double-ring stub-loaded CSRR (right) (grey region is metal, white region is substrate).

resonator is given as,

$$f_0 = \frac{k}{\sqrt{L}} \tag{4}$$

where k is material dependent constant. L denotes the perimeter of octagonal loop resonator.

Two independent frequencies will offer by two separate CSRR. By substantial increase in the electrical length of CSRR though the frequency will also increase.

COMPACT SIW DUAL BAND BANDPASS FILTER STRUCTURE LOADED WITH CSRRS

In this section a single pole dual band bandpass SIW filter structure loaded with octagonal shape CSRRs is discussed in detail. The preliminary theory about the filter design by using resonator with resonant modes becomes the basic transmission line stepped-impedance or loaded stub configuration theory and network analysis. Recently, different CSRR structures have been introduced and successfully integrated with SIW structure to obtain the single/multi-pass characteristics having a minimum size as reported in [5], [12]–[14], [17], [20]–[23]. The metamaterial characteristics such as negative permittivity or composite right/left handed of microstrip line have been obtained using CSRR structure [7], [8].

Single pole dual-passband SIW bandpass filter

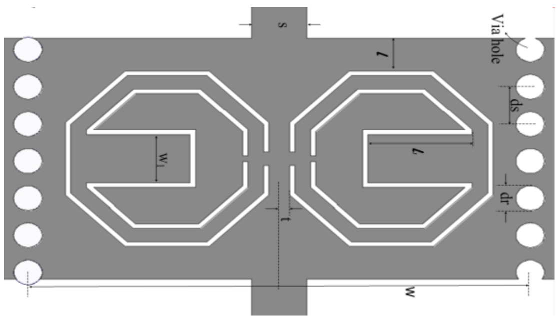


Figure 3: Layout of the SIW structure with a pair of resonators for proposed single pole dual-band filter (all dimensions are in mm: W=7, l_1=2.9, ds=1.45, dr=0.8, t=0.25, w_1=1.567, l=0.4358)

Figure 3 depicts the layout of the proposed dual resonance unit cell is etched on the SIW top. The microstrip feed line is used to excite this integrated structure. This combined structure can get tight coupling due to double ring with SIW. However, these filters are made of distributed elements that show some losses and are described by the unloaded quality factor Q higher than 153. If a finite Q is considered in the synthesis, the fundamental mode is excited [14]. The center to center separation which is being calculated in such a way that it just excites the TE_{110} mode at the test frequency

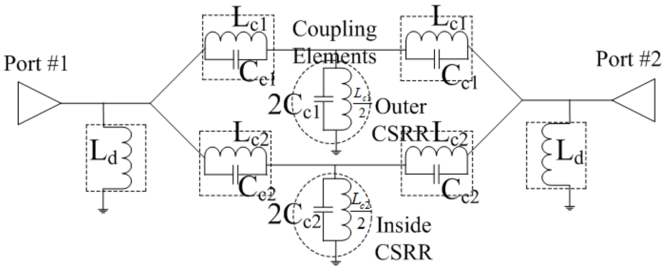


Figure 4: Equivalent circuit of single pole dual band SIW filter embedded with CSRR.

Table 1: Lumped-element value of the circuit model

L_{c1} (nH)	C_{c1} (pF)	L_{c2} (nH)	C_{c2} (pF)	L_d (nH)
1.755	0.4507	0.5829	0.55305	5.9

The electrical coupled CSRR pair is designed with the help of a shunt connected resonators comprised of C_{c1} and an inductor L_{c1}; there is a slot coupling amongst the SIW and CSRR, viz inductive and capacitive coupling through the split of the ring. The modelled structure as designed initially from the equivalent circuit (Figure 4) of the filter incorporating a pair of resonator CSRR having single pole is shown in Figure 3. Lumped element value of the circuit is reflected in Table 1. The response of the filter is shown in Figure 5.

The response curves for bandwidth, insertion loss, roll off rate and transmission zero position have been analyzed. The structure simulation was carried using Ansoft's High Frequency Structure Simulation (HFSS) and its equivalent circuit parameter is extracted using Advance Design System (ADS).

The measure result obtained from the hardware through 8753ES network analyzer provides a good agreement with the simulated result. Figure 5a & 5b shows the result of measured reflection (S_{11}) and transmission (S_{21}) coefficient with HFSS and circuit simulation respectively. The measured s-parameter has good agreement with HFSS and circuit simulation displayed in Figure 5c. During single pole measurement the two pass band (3.725-4.208) GHz (483 MHz) and (6.019-6.169) GHz (150 MHz) with center frequency 3.97 GHz and 6.2 GHz respectively are obtained. The insertion loss is estimated 0.6 dB in the first pass band and 1.76dB in second pass band. The roll off rate -23.04 dB/GHz and the transmission zero at 5.57 GHz at stop band.

Transmission zeros are estimated by a value of the circuit component that plays a vital role for coupling between resonators and SIW via. The transmission zero can be located

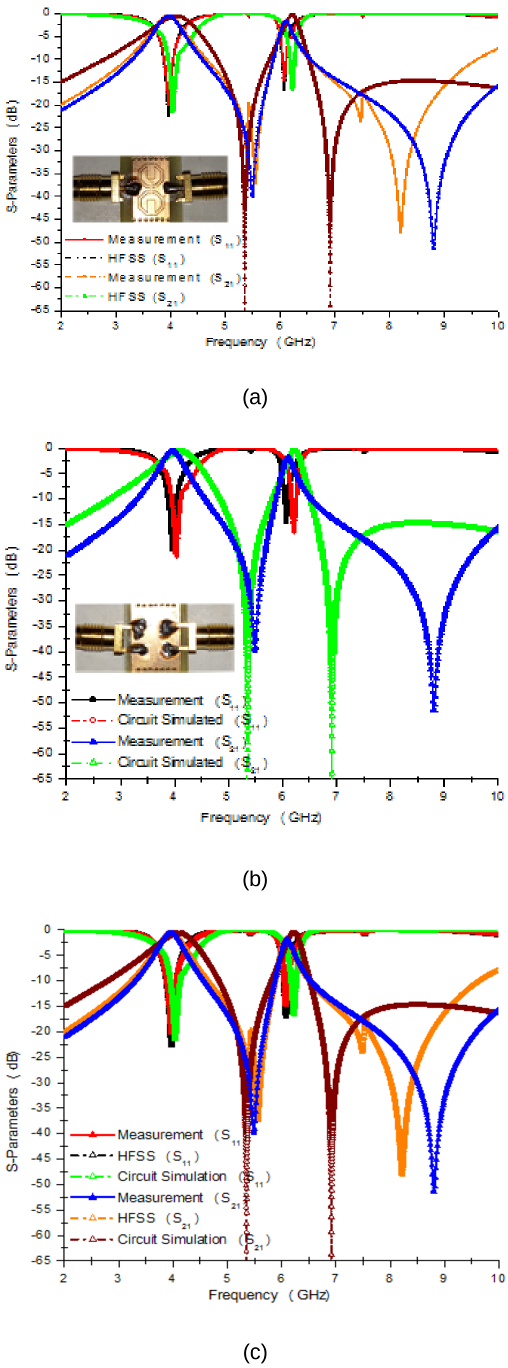


Figure 5: Response of simulated and measured S-parameter (a) Single pole infix measured and HFSS simulated S-parameter. (b) Measured result and circuit simulated S-parameter. (c) Complete response measured, HFSS and Circuit Simulated S-parameter.

to desired position by adjusting properly selecting the value of the circuit component(s) and the dimensions related to a structure which provides a place to those values. In the next section double pole dual-passband SIW bandpass filter is explained.

Double pole dual-passband SIW bandpass filter

To enhance previous performance parameter an array of the set of the resonator has been added to attain the two poles dual-passband filter is expressed in Figure 6. The array containing unit cells are comprised with two pairs of single ring CSRR. These symmetric single ring CSRR are integrated on the metal surface of the waveguide. The proper orientation of split of ring slot is placed face to face which leads to strong coupling between the waveguide and the CSRR. Two independent resonant frequencies are generated in which the interior slot ring has a higher frequency at 6.2 GHz. while the outer ring produces a lower one as 3.97 GHz. If distance between the resonators is increased, the resonating frequencies will approach each other and corresponding bandwidth will become narrower at a higher frequency. The resonant frequency will be wide if the distance between the resonators becomes 0.1mm. The resonant frequency wider and becomes narrower at the lower and higher frequency respectively. Only one single resonant frequency will be detected (the lower one) in the observed frequency band if the resonators are mutually connected.

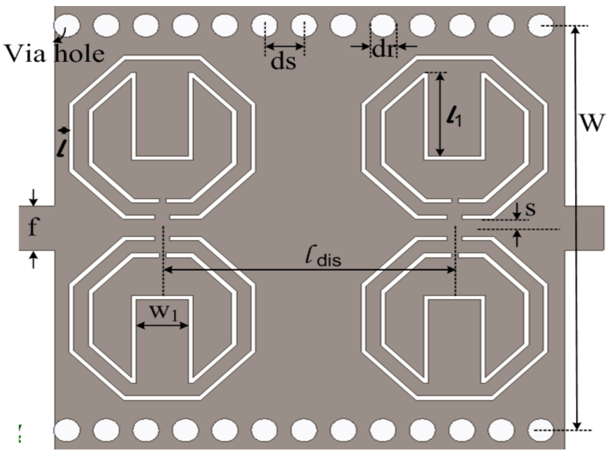


Figure 6: Top view of our proposed Layout of the two pole bandpass SIW filter

Table 2: Geometrical dimension of the dual band SIW-CSRR Filter

Symbol	Value (mm)	Symbol	Value (mm)	Symbol	Value (mm)
d_1	0.45	b	1.87	s	0.25
d_2	0.2	g	0.179	W_1	1.567
c_1	0.125	l_1	2.9	l_{dis}	8.88
c_2	0.125	ds	1.45	f	1.53
a	2.35	dr	0.8	l	0.4358
W	7				

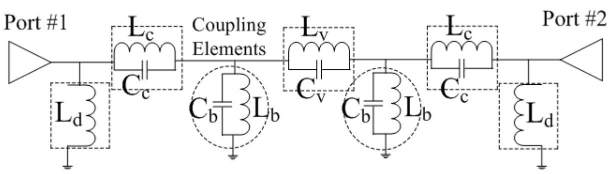
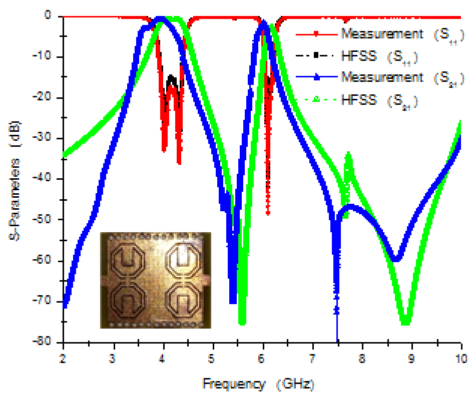


Figure 7: Equivalent circuit of dual pole dual band SIW filter

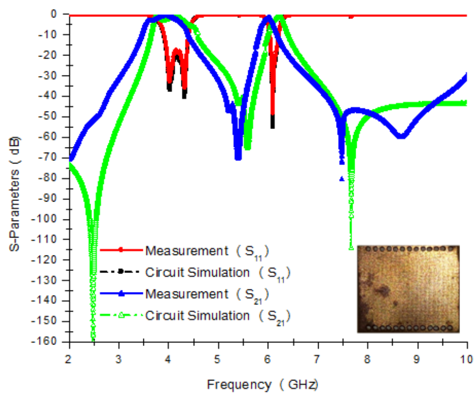
Table 3: Lumped-element value of the circuit model

L_c (nH)	C_c (pF)	L_v (nH)	C_v (pF)	L_b (nH)	C_b (pF)	L_d, (nH)
0.3349	4.3103	1.6807	2.638	0.3229	2.1598	4.5018

The desired geometrical dimension related to the double pole dual-passband SIW bandpass filter is shown in Table 2. The equivalent circuit of this filter is in Figure 7 and their lumped element value is in Table 3. The simulated and measured result of the filter is shown in Figure 8. It can be seen from the S-parameter result of the proposed filter, the dual-passband characteristics are obtained. The filter is designed for the central frequency of 3.97 GHz.



(a)



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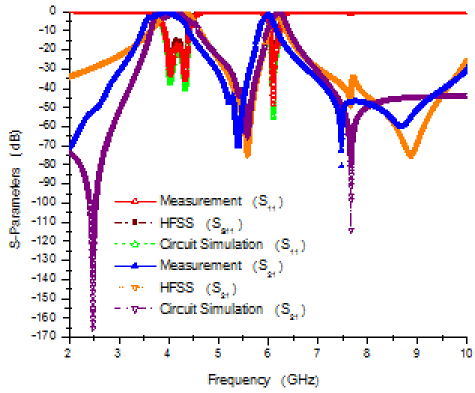

(c)

Figure 8: S-parameter result of proposed filter (a) Dual pole infix measured and HFSS simulated S-parameter. (b) Measured result and circuit simulated S-parameter. (c) Complete response measured, HFSS and Circuit Simulated S-parameter.

The response curve for bandwidth, insertion loss, roll off rate and transmission zero position has been simulated on the structure using HFSS and equivalent circuit parameters using ADS. The simulation results are validated with measured results which have been reflected in Figure 8.

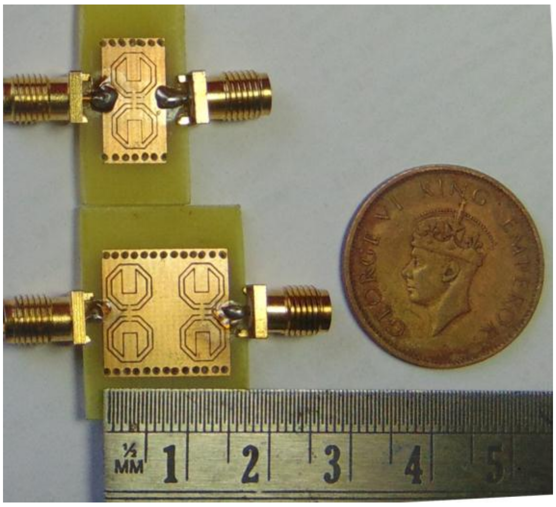

Figure 9: Top view of the fabricated filter

Figure 9 present photographs of a prototype manufactured with photolithography process on a printed-circuit board to observe and analyze single and double pole dual-passband SIW bandpass filter using substrate material Rogers RT/duroid 5880 (tm) with a dielectric constant of $\varepsilon_r = 2.2$; tanδ = 0.002 with a thickness of h = 0.508mm, and a metallization thickness of t = 0.035mm. While observation these two individual rings of CSRR offer two relative independent resonant frequencies. The external ring has smaller frequency though internal has a higher frequency. In the inner slot ring, a U-extension is proposed to increase the total slot length hence proper adjustment of the resonance frequency. A minimum resolution is proposed for inter resonator and amongst the width and separation of the rings restricted due to limitation as imposed by machining process during fabrication of the component. The performance of the proposed filter in terms of centre frequencies, fractional bandwidth, insertion loss and size are compared with other dual-passband filter as reported in the literature and is summarized in Table 4.

Table 4: Comparison between proposed and reference

Referen-ce	Center frequen-cies (GHz)	Fractional Bandwidth (%)	Insertion loss (dB)	Size (λ_g^2)
Propose Work	3.97 & 6.1	**14.27** & 2	**0.7** & 2	**0.138×0.137**
[5]	20.5	3.41 & 3.90	0.9 & 1	1.419 × 0.619
[13]	4.66 & 5.8	— — —	1.6 & 2.3	0.182 × 0.146
[17]	4.22 & 5.96	6.31 & 4.05	1.82 & 2.13	0.144 × 0.122
[20]	2.4 & 5	1 & 1	1.47 & 1.01	0.407 × 1.017
[22]	30.3 & 39.3	Both 6	4.5 & 5.1	0.927 × 0.882

From the comparative result, it is evident that the size of the filter is compact leading to cost-effective. The simulations and measurements are accomplished by using HFSS, ADS and 8753ES network analyzer. Figure 5(a)-(c) and Figure 8(a)-(c) depicts good agreement between the simulated and measured results. The proposed band pass filter (BPF) yields two passbands (3.82-4.39) GHz (566 MHz) and (6.18-6.31) GHz (123MHz), which is located at center frequency around 3.97 GHz and 6.2 GHz respectively. The first passband is centered at 3.97 GHz, with the insertion loss 0.7dB and bandwidth of 14.27%, the return loss is greater than 15dB. The transmission zero is realized close to the passband edges at 5.59 GHz, which greatly improve the skirt selectivity. The second passband is located at 6.2GHz and 3dB bandwidth is 2%. There is a significant improvement in deduction in the insertion loss and increase in the bandwidth. The simplicity of the design using the software is another advantage as compared to complexity as observed in others reported filters by various authors.

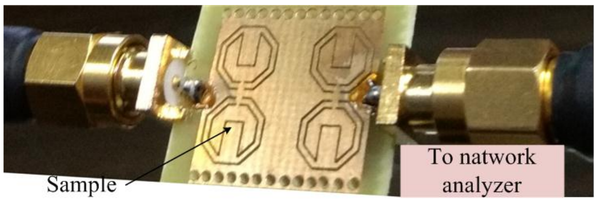

Figure 10: Experimental setup for measuring the fabricated Microstrip-fed BPF

The proposed SIW filter with four unit of CSRR structure is designed to enhance the rejection bandwidth and to tune the resonance frequency of dual resonators by multiple tuned resonator approach as reported in [19]. It also enhances the coupling between the resonators and dimensions of two pole filter by using HFSS. Transmission response and the performances of the fabricated microstrip-fed BPFs have been measured by using a Anritsu VNA Master Model (MS2038C) (1-20 GHz, Anritsu Corp.) as shown in Figure 10. It has good filtering responses in comparison to single pole filter with broader bandwidth. This gives strong effective coupling amongst this two proposed CSRR. Transmission zero is observed in both the upper and lower stop band and thus has good selectivity.

CONCLUSION

A new miniaturized SIW loaded CSRR dual Band Pass filter is proposed using octagonal structure. The simulated results obtained by HFSS and circuit simulation are close agreement with the measured result. The proposed filter yields compact size with improved performance at low cost system. The filter has $0.138\lambda_g \times 0.137\lambda_g \times 0.004\lambda_g$ dimensions and achieve insertion loss less than 0.7 dB in the first pass band. The suggested filter can be scaled easily to other frequency for low insertion and high Q band pass filters. The proposed filter finds its wide applications in C band of microwave communication system.

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