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A W-band Substrate Integrated Waveguide (SIW) Bandpass Filter at 95 GHz for Millimeter Wave Applications

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Abstract
One of the most suitable option for millimeter-wave integrated circuits and systems implementation is Substrate Integrated Waveguide (SIW) Technology. This paper reports a wide band Substrate Integrated Waveguide bandpass filter for W-band applications. The proposed filter is designed by implanting iris discontinuities in periodic topology in both horizontal and vertical directions inside the substrate. The simulation and parametric evaluation of the anticipated filter is done by CST Microwave studio suite software. The performance evaluation and parametric study reveals that due to insertion of metallic holes inside the structure in periodic arrangement with optimum diameter and adequate spacing supports in minimization of losses and obtaining wide bandwidth. The bandpass performance of the proposed filter exhibits an insertion loss (S_{21}) better than 2.1 dB and return loss (S_{11}) less than 27 dB at 95 GHz center frequency. The 3-dB bandwidth obtained is 15 GHz. The proposed structure is appropriate for use in millimeter-wave and RADAR operations.

Keywords Millimeter-wave · RADAR · W-band · Substrate Integrated Waveguide · 95 GHz · Bandpass filter · Periodic pattern

1 Introduction

For high quality millimeter-wave and microwave communication systems, there is a great need to deploy low cost, low weight, small size, high capacity and of good performance characteristics filters. Conventional waveguide filters using metallic waveguides, co-axial lines and circular waveguides exhibit low loss, excellent reliability and great power handling capability. However, waveguide filters are massive, expensive, and challenging to integrate with other planar and non-planar circuits. Various planar circuits such as microstrip lines and co-planar waveguides (CPWs) also exhibit low cost, small size and good integration with other planar circuits. However, sometimes these filters are unable to provide desired performance. To meet the desired requirements of high performance and low cost, special type of filters have been designed known as Substrate Integrated Waveguide

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(SIW) filters. SIW inherits many advantages such as low cross talk, low loss, high capacity, ease of integration, low weight and good quality factor [1].SIW structure is designed with linear patterned array of metallic cylindrical holes embedded inside the substrate. Cylindrical holes/vias are of certain diameter with adequate spacing. This leads to guided wave structure and electromagnetic waves are well confined along two parallel walls of the waveguide. The SIW planar circuits behaves like a rectangular waveguide [2, 3]. So, all concepts of waveguide theory can be materialized on SIW circuits. SIW technique has been tested on various microwave circuits including power dividers [4], antennas [5], reconfigurable antenna [19], diplexers [6], couplers [7], filters [8, 9] etc. The technique is more attractive for designing high frequency antennas and filters design. Many papers have been published to demonstrate the properties and capacities of Substrate Integrated Waveguide (SIW) filters. More focus is made on making the size compact and achieving steep skirt characteristics of the SIW filters. In order to reduce the size of circuit, substrate integrated waveguide(SIW) filters using various multilayered low temperature co-fired ceramic(LTCC) technology [12], printed circuit boards (PCB) process, folded SIW cavities (half folded and double folded) [13], meta-material resonators such as complementary split ring resonators (CSRRs) [11], defected ground structures (DGS) [10] etc. are designed. Filters in ultra wide band and high frequency range are also investigated. In this paper, a W-band SIW band-pass filter at 95 GHz center frequency is proposed, which is suitable for use in millimeter wave applications. The structure is designed by inserting metallic holes in periodic topology with an adequate spacing and optimum diameter for maximum coupling of energy to obtain wide bandwidth and to minimize the losses.

2 Realization of SIW Filter

The SIW system is composed of rows of metallic cylindrical cavities that are embedded in the dielectric material at periodic intervals. Only TE_{n0} modes are allowed to propagate in this configuration because of the metallic surfaces that bound the SIW [14, 15]. The spacing or pitch length p between adjacent holes/vias and their diameter d are the most essential characteristics. The Substrate Integrated waveguide structure performs the same as the rectangular waveguide for specific values of “p” and “d” and the radiation leakage can also be minimized. The waveguide filters can be designed by incorporating standard irregularities in the rectangular waveguide structure. One of such achievable metallic discontinuities in the rectangular waveguide structure is depicted in Fig. 1.

Iris discontinuities produce a symmetric induction slots and cavity resonators are inserted between them. The size of the metallic cavities regulates the coupling between cavity resonators. Circular post is represented by equivalent circuit consisting of two equivalent capacitances X_s & X_p as illustrated in Fig. 2a.

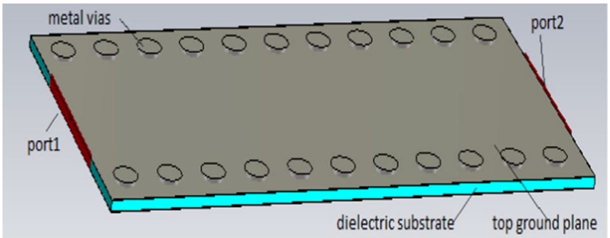
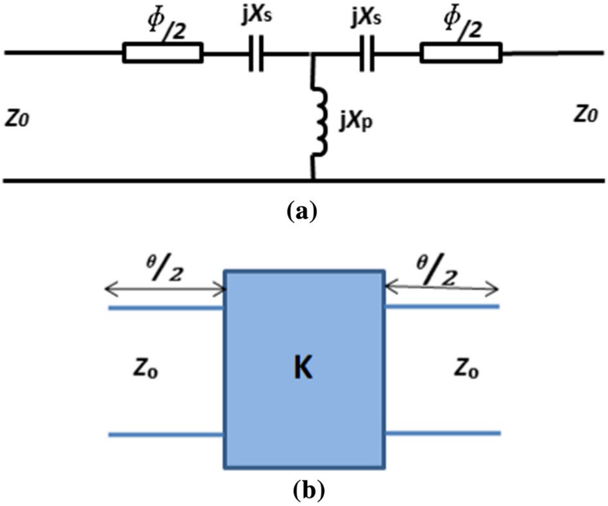


Fig. 1 Substrate Integrated Waveguide (SIW) basic structure

Fig. 2 **a** Equivalent circuit **b** Impedance inverters



These induction cavities that connect SIW transmission lines to each other, as per Fig. 2b, perform as impedance inverters [9]. As a result, the SIW filter design technique with iris discontinuities is simplified in order to obtain the inverter characteristic impedance and spacing between symmetrical metallic walls [15].The basic framework of a microwave filter is a lumped parameters low-pass filter. The attributes of low-pass prototype are translated into almost all types of high-pass, band stop and band-pass filters. The Chebyshev low-pass filters have a wide range of applications due to its simple structure, wide band, and sharp edges. In comparison to conventional inductive metal posts, an inductive bridge is the ordinary T-network, which is made up of lumped elements such as capacitance, inductance, and so on (see Fig. 3).

In Fig. 3, for a filter with N reactive components, the component values are assigned from g_0 at the generator impedance to g_{N+1} at the load impedance. The components choice between series and shunt connections and g_k is inductance for series inductors and capacitance for shunt capacitors (k = 1 to N), $g_{N+1=}$ load resistance parameters if g_N is a shunt capacitor, load conductance if g_N is a series inductor.

For a bandpass filter with Chebyshev frequency characteristics, the normalized characteristic impedance using an impedance inverter can be calculated as follows [16]:

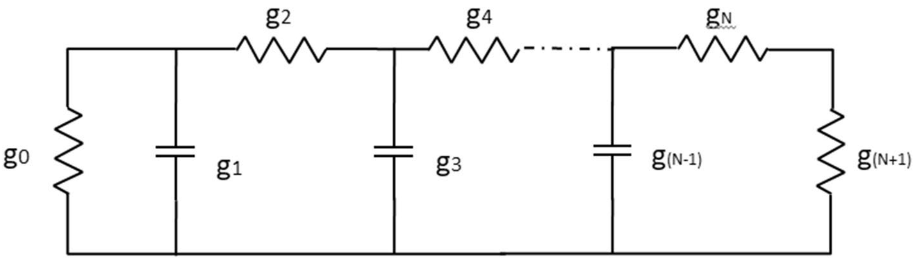


Fig. 3 Low pass filter prototype

$$\Delta = \frac{\lambda_{g1} - \lambda_{g2}}{\lambda_{g0}} \tag{1}$$

$$\frac{k_{0,1}}{Z_0} = \sqrt{\frac{\pi.\Delta}{2.g_0 g_1.\Omega}} \tag{2}$$

$$\frac{k_{N,N+1}}{Z_0} = \sqrt{\frac{\pi.\Delta}{2.g_N g_{N+1}.\Omega}} \tag{3}$$

$$\lim_{j=1 to j=N-1} \frac{K_{j,j+1}}{Z_0} = \frac{\pi\Delta}{2\Omega} \frac{1}{\sqrt{g_i g_{i+1}}} \tag{4}$$

$$\lambda_{g0} = \frac{\lambda_{g1} + \lambda_{g2}}{\lambda_{g0}} \tag{5}$$

where g_i's $(0 < i \leq N + 1)$are the coefficients for the Chebyshev response lowpass filter elements, Δ is the fractional bandwidth of the guided wavelength, Z_0 is the characteristic impedance of the transmission line, Ω is the normalized lowpass frequency, λ_{go} is guided wavelength of center frequency, λ_{g1} and λ_{g2} are the guided wavelengths for the upper and lower frequencies of the bandpass filter, k is the energy coupling factor between resonators provided by impedance inverters [where $k_{i,\ i+1} = (0 \leq i \leq N)$] [17].

The values of Chebyshev low pass filter elements can be computed using the following formula:

$$g_{N+1} = 2k^2 + 1 + 2k\sqrt{1 + k^2} \tag{6}$$

$$g_k = \frac{4a_{k-1}a_k}{b_{k-1}g_{k-1}} \tag{7}$$

$$a_k = \sin\frac{2k - 1.\pi}{2N} \tag{8}$$

$$b_k = \sinh^2\frac{\beta}{2N} + \sin^2\frac{k\pi}{N} \tag{9}$$

$$\beta = \ln\frac{\sqrt{1 + k^2} + 1}{\sqrt{1 + k^2} - 1} \tag{10}$$

$$g_1 = \frac{2a_1}{\sinh\frac{\beta}{2N}} \tag{11}$$

where a_k and b_k are the coupling coefficients and β is the phase constant,. Table 1 shows several numeric g_k values for equal ripple filters N up to 5.

Table 1 Values of g_k with $k^2 = 0.023$

k	N			
	2	3	4	5
1	0.84	1.03	1.11	1.15
2	0.84	1.15	1.35	1.37
3		1.03	1.77	1.97
4			0.82	1.37
5				1.15

The practical length of the cavity resonators can be measured by calculating the characteristic impedance values of the impedance inverters as given below [17]:

$$\frac{X_{j,j+1}}{Z_0} = \frac{\frac{K_{j,j+1}}{Z_0}}{1 - \frac{K_{j,j+1}}{Z_0}^2} \tag{12}$$

The phase shift angle and electrical length of the resonators are determined by:

$$\varphi_i = \pi - \frac{1}{2}\left[\tan^{-1}\left(\frac{2X_{j-1,j}}{Z_0}\right) + \tan^{-1}\left(\frac{2X_{j,j+1}}{Z_0}\right)\right], L = \frac{\varphi_i \lambda g_0}{2\pi}(1 \leq j \leq N) \tag{13}$$

where φ_i $(1 \leq i \leq n)$ is the phase shift angle of the resonators and L is the length of the resonators.

The T equivalent circuit model of this discontinuity is illustrated in Fig. 2(a). The values of its parameters depend on iris discontinuity position, frequency, and geometric dimensions. The T-equivalent circuit parameters are calculated using equations given below [17]:

$$\varphi = -\tan^{-1}\left(2X_p + X_s\right) - \tan^{-1} X_s \tag{14}$$

$$jX_s = \frac{1 - S_{12} - S_{11}}{1 - S_{11} + S_{12}} \tag{15}$$

$$jX_p = \frac{2S_{12}}{\left(1 - S_{11}\right)^2 - S_{12}S_{12}} \tag{16}$$

$X_s = \frac{X_p}{Z_0}$ and S_{ij} $\lim_{i,j=1,2}$ are corresponding scattering parameters in each iris discontinuity Eqs. (12) to (16) are used to evaluate the physical attributes of the iris waveguide filter, and the equivalent SIW parameters are computed as [17]:

$$L_{\mathrm{SIW}} = L_{\mathrm{eff}} + \frac{d^2}{0.95p} \tag{17}$$

$$W_{\mathrm{SIW}} = W_{\mathrm{eff}} + \frac{d^2}{0.95p} \tag{18}$$

where W_{siw} is the width of the SIW, d is the diameter of holes, the pitch length p between adjacent holes provided that $d < \lambda_O\sqrt{\in_r}$ and $p < 4d$ with ε_r relative permittivity and L_{eff} & W_{eff} are the effective length and width of the analogous rectangular waveguide.

The dispersion characteristics of metallic rectangular waveguides are known to be relatively similar. In particular, the electromagnetic field distribution is TE_{10} [1], the SIW is related to the traditional rectangular waveguide filled with the same dielectric between two metal plates. The cut-off frequency of the waveguide is given as:

$$f_{c10} = \frac{c}{2W_{\mathrm{eff}}\sqrt{\in_r}} \tag{19}$$

The anticipated SIW filter structure is based on approximately calculated parameters. The filter model is simulated and developed using a full wave electromagnetic modeling. Using above design equations the structure length and width is proposed using equation no. 17 and 18.

3 Loss Minimization Criterion

When a device is operating in millimeter–wave frequency range, three loss mechanisms occur in the SIW structure. The radiation losses, conductor losses and dielectric losses are all seen in the SIW structure. Different geometrical factors, such as substrate thickness and pitch length, are used to minimize these losses [16].There are few design conditions to reduce the losses. These are as follows:

$$\frac{d}{p} \geq 0.5 \tag{20}$$

$$d = 0.2\lambda_g \tag{21}$$

where λ_g is guided wavelength. Guided wavelength is given in Pozar M. David [14]:

$$\frac{2\pi}{\sqrt{\frac{\omega^2 \in_r - \left(\frac{\pi}{a}\right)^2}{c^2}}} \tag{22}$$

where ω is the angular frequency and a refers to the rectangular waveguide width. The pitch length should be kept small to diminish conductor losses and thickness of post is made optimum to organize radiation losses [18–22]. Dielectric losses can be decreased by accurate choice of substrate. The proposed filter is designed by embedding metallic vias on the top layer of substrate in periodic pattern to achieve wide band response at 95 GHz center frequency as shown in Fig. 4. The inserted periodic patterns allow various electric and magnetic coupling mechanisms inside the structures. The feed line w_f should be of appropriate width for maximum coupling of energy from input port to output port. The width of the structure W_{siw} is calculated using Eq. (18).

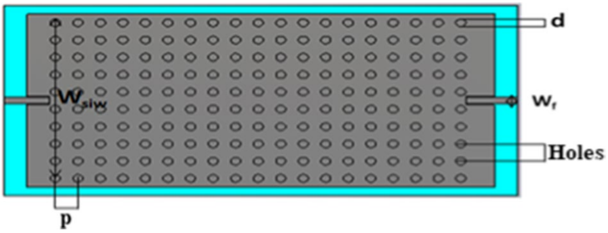


Fig. 4 Substrate Integrated Waveguide (SIW) bandpass filter

4 Estimated Parameters and Simulated Responses

The parametric evaluation and simulation of filter is done by computer simulation technology (CST) software Microwave studio suite. Various parametric studies have been made to get the desired performance at 95 GHz center frequency. The most effective and significant response is attained by implanting metallic holes in cyclic pattern with particular diameter and suitable spacing along the horizontal and vertical dimensions inside the structure. The SIW filter is designed by using a substrate with dielectric constant $\in_r$ of 2.2 and height h of 0.787 mm. The proposed filter structure is excited by open-ended microchip lines in various topologies. Slots are etched to increase the energy fed to the structure. The energy coupled to the SIW structure is regulated by both the length and the position of the slots. The appropriate slot allocation modifies the fractional bandwidth from 1% to 14.9%. Energy is magnetically coupled from feed line to SIW resonator. So, in order to achieve maximum bandwidth co-planar waveguide is inserted inside the SIW structure. The optimum dimensions of the proposed SIW bandpass filter structure are obtained by using mathematical equations given above in the proposed filter design. Various parametric values obtained are shown in Table 2.

4.1 Effect of the Change in Vias Diameter on Bandpass Filter Response

Table 3 shows the effects of changing the metallic holes diameter on bandpass filter responses including return loss, insertion loss, 3-dB bandwidth and fractional

Table 2 Parametric values of the substrate integrated waveguide structure

Parameters	W_f	h	W_{siw}	L_{siw}	d	p
Values (mm)	1.84	0.787	2.1	5.34	0.45	1.5

Table 3 Comparison table showing change in responses by changing holes diameter

S. no	Diameter of Vias (mm)	Return loss (S_{11}, dB)	Insertion loss (S_{21}, dB)	Bandwidth (GHz)	Center frequency (f_c)	Fractional bandwidth (FBW) (%)
1	0.44	12	2.8	9	100.5	8.9
2	0.45	27	2.1	15	94.2	15.9
3	0.46	25	2.6	15	94.2	15.9

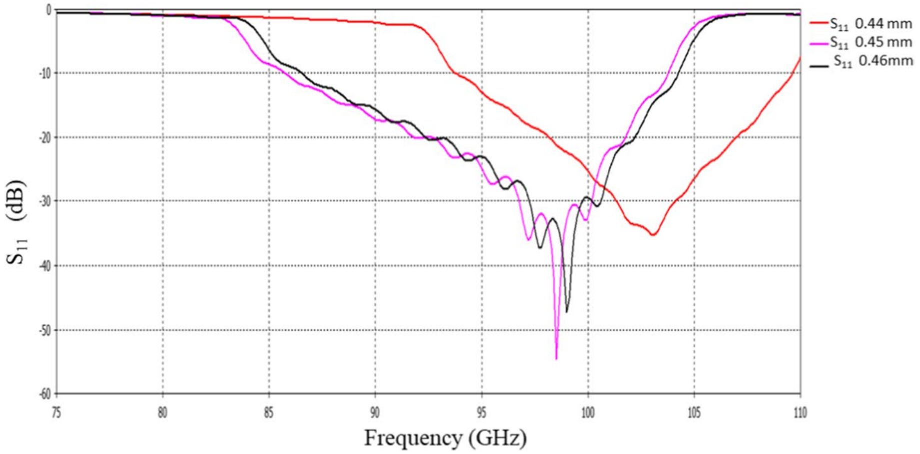


Fig. 5 SIW bandpass filter depicting return loss (S_{11}) by varying diameters of holes

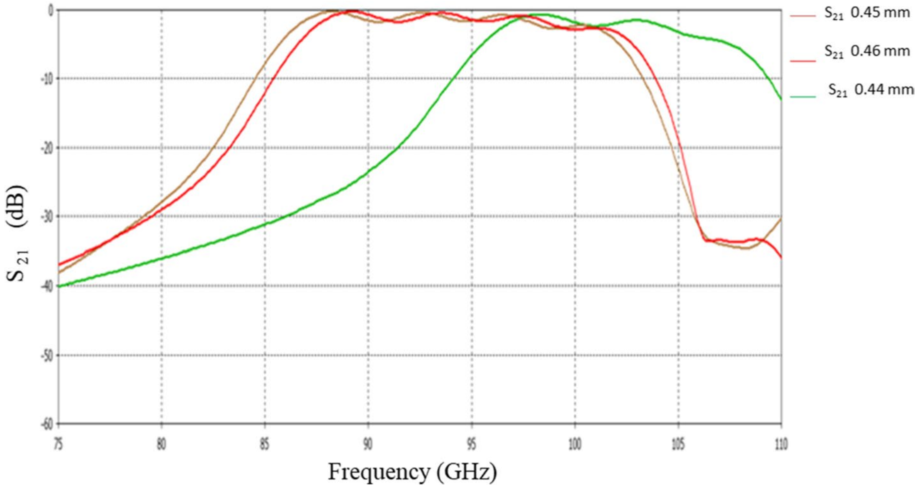


Fig. 6 SIW bandpass filter depicting insertion loss (S_{21}) by varying diameters of holes

bandwidth. It is proved from the studies that if the diameter of vias is kept small, then there will be low losses both return loss as well as insertion loss.

The comparison curves of return losses (S_{11}) by varying the holes diameters are depicted in Fig. 5. When diameter of all holes is taken as 0.45 mm, the response is shown by purple coloured curve depicting return loss less than 54.6 dB which is best in comparison with curves traced when holes diameters are taken as 0.44 dB and 0.46 dB, respectively. Similarly, return losses (S_{21}) comparisons are illustrated in Fig. 6. The bandwidth obtained is 15 GHz with insertion loss less than 2.1 dB when hole diameter is taken as 0.45 mm.

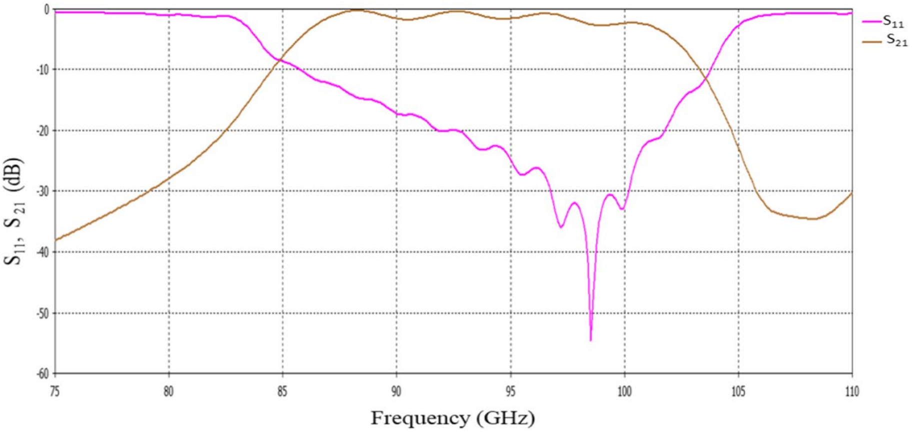


Fig. 7 SIW structure illustrating bandpass filter response

Fig. 8 Fabricated view of the SIW filter

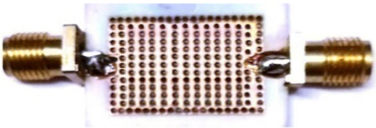


Figure 7 illustrates the SIW bandpass filter response in terms of S_{11} and S_{21} parameters. S_{11} represents the return loss 54.6 dB and an insertion loss S_{21} better than 2.5 dB. The 3-dB bandwidth of filter obtained is 15 GHz centered around 95 GHz.

For the entire 3 dB bandwidth from 87 to 102 GHz, the filter exhibits a uniform return loss (S_{11}) 15 dB and an insertion loss 2.5 dB. It is observed that 0.45 mm is the optimum diameter of holes for better responses.

4.2 Fabrication and Measurement of the SIW Filter

The material dielectric constant is 2.2. The Roggers 5880 substrate is chosen for its outstanding mechanical and electrical capabilities, as well as its incomparable cost performance. When compared to PTFE and other commonly used microwave laminates, Roggers 5880 has the minimal insertion loss. The fabricated filter structure is represented in Fig. 8.

The simulated and measured outcomes are in close agreement with each other, as shown in Fig. 9. The proposed substrate integrated waveguide bandpass filter shows an improvement in bandwidth as reported by Min Han et.al. [18]. The bandwidth is improved due to periodic discontinuities inserted inside the structure.

5 Conclusion

In this article, a wideband Substrate Integrated Waveguide (SIW) bandpass filter is investigated at 95 GHz center frequency. The structure is designed by implanting metallic holes in cyclic topology inside the substrate in both horizontal and vertical directions. The

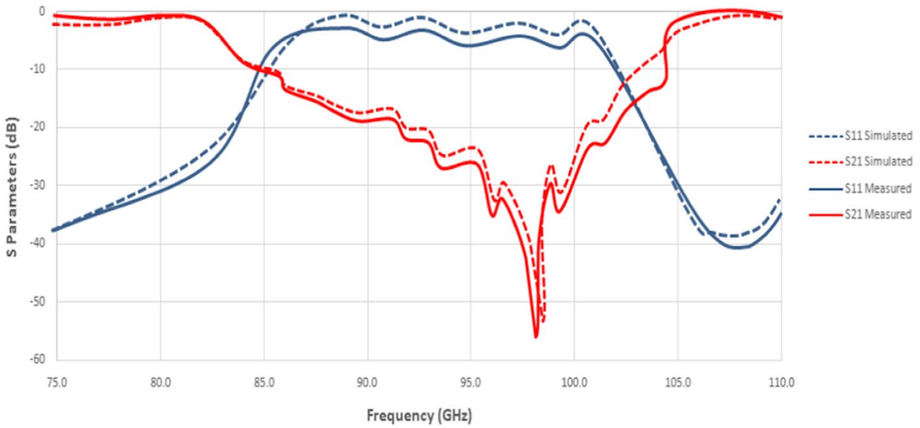


Fig. 9 Simulated and measured results of fabricated filter

simulated results exhibit a return loss less than 27 dB and insertion loss better than 2.1 dB over the pass band and offers 3-dB bandwidth of 15 GHz. Parametric study reveals that insertion of holes inside the substrate in periodic topology have successfully led to offer wide bandwidth filter, sharp skirt characteristics and low losses. The SIW filter developed here is appropriate for millimeter-wave applications.

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