Design of Substrate Integrated Waveguide Pass Filter at [33-75] GHz Band

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***Abstract*—This article presented the design of two filters SIW (Substrate Integrated Waveguide) in two different bands. Their conceptions were made by two different topologies. The first SIW filter with circular inductive post in the band [33-50] GHz on an RT / Duroid 5880 substrate permittivity 2.2, the simulated results of this filter have shown that the insertion loss lower than -0.4 dB within 3.5% bandwidth around 41.7 GHz and the return loss is better than -15 dB between 41.1 GHz and 42.4 GHz. The second SIW filter with iris in the band [50-75] GHz on an NY9217 (IM) substrate permittivity 2.17, the simulated results of this filter have shown that the insertion loss lower than -0.35 dB within 19% bandwidth around 62 GHz and the return loss is better than -15 dB between 60 GHz and 66.3 GHz. The compatibility with planar circuits is provided via a specific microstrip transition (microstrip tapered transitions).**

Keyword-Rectangular Waveguide, Substrate Integrated Waveguide, Microwave Filters, Transition, SIW-Microstrip Technology

I. Introduction

A High selectivity, low insertion loss, small size and limited cost are so many essential questions in the design and the manufacturing of microwave circuits. Unfortunately, the traditional technology, either planar or non-planar, is incapable to provide all these characteristics at the same time. In fact, the rectangular waveguides present low insertion losses and good selectivity. However, their production is costly and their integration with other planar circuits requires a specific transition.

For planar circuits have a low quality factor, but they have a good compatibility and low cost manufacturing. These constraints led us to use the SIW technology to combine the respective advantages of the technologies previously mentioned.

This concept associates the use of planar technology microstrip and the functioning of cavities in which are going to exist volume modes [1]. Technically, cavities are included in the substratum and are delimited for the upper and lower faces by the metal plane and for the side faces by rows of metallic holes. This vias have a diameter and spacing small to appear as electric walls [1-5]. However, the change of electrical walls by metallic holes implies that certain modes cannot resonate.

The SIW (Substrate Integrated Waveguide) structures have been of great interest and with a specific transition that this technology is compatible with some planar technologies [6].

However, the SIW has been applied successfully to the conception of planar compact components for the microwave and millimeter wave applications. Such as filters [2, 5, 8, 9, 11], numerous applications were made on SIW filters for millimeter and sub-millimeter [5, 8, 9, 11, 12]. The results show that the quality factor greater than what can be obtained with planar technology.

II. Design of the SIW Technology

A substrate integrated waveguide (SIW) is made of metallic via-hole arrays in the substrate between top and bottom metal layers replacing the two metal sidewalls are shown in Fig. 1.

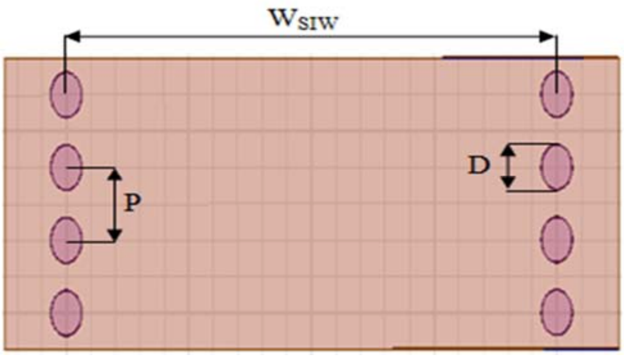


Fig. 1. SIW Guide

The dimension D corresponds to the diameter of vias and P the distance between two adjacent vias center in center. W_{SIW} Is the real distance between the two rows of vias.

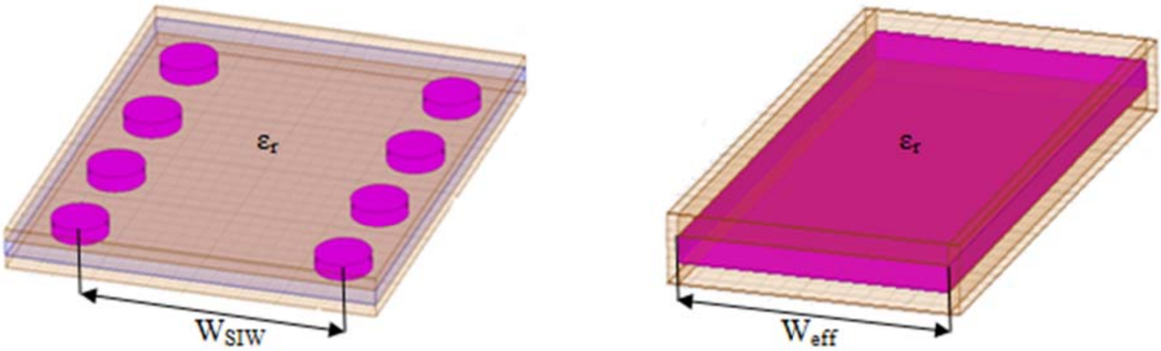
The width and the length of the SIW guide was found by equations 1 and 2 provided that P < λ0 (ε_r/2)1/2 and P < 4D with ε_r relative permittivity [1-3]:

$$W_{eff} = W_{SIW} - \frac{D^2}{0.95P} \quad (1)$$

$$L_{eff} = L_{SIW} - \frac{D^2}{0.95P} \quad (2)$$

The propagation properties in the SIW and in the conventional metallic rectangular waveguide are very similar. In particular, the electromagnetic field distribution is TE_{10} [1], the SIW guide is similar to that of a conventional rectangular waveguide filled with the same dielectric of width W_{eff}.

$$f_{C_{10}} = \frac{c}{2W_{eff}\sqrt{\varepsilon_r}} \quad (3)$$



(a) (b)

Fig. 2. (a) SIW Guide. (b) Equivalent rectangular waveguide

III. Theoretical Study of Band Pass Filter and Proposed Transitions

Generally, a microstrip transition is used to interconnect SIW to the planar transmission lines. She is used to match the impedance between a microstrip line and the SIW. The physical characteristics of microstrip line (the width W_M) and dimensions (width W_T and length L_T) of a transition are widely detailed in [4, 6]. In this study, we used the tapered transitions as shown in Fig. 3.

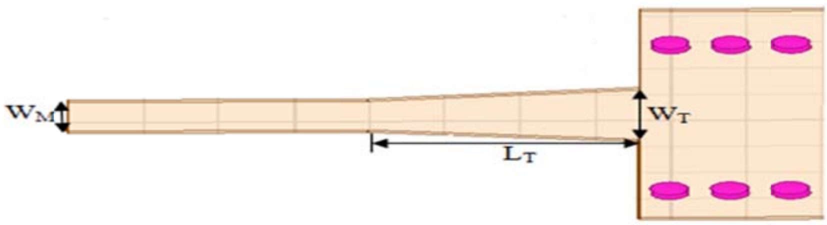


Fig. 1. SIW Guide with tapered transitions

The microwave band-pass filters are presented by an equivalent circuit [7]. This circuit consists of impedance inverters and parallel resonant circuits. The number of the resonators or the order of the filter is determined by equation 4 applicable in the case of Chebyshev synthesis [7].

$$n \geq \frac{\cosh^{-1}\sqrt{\dfrac{10^{0.1L_{As}}-1}{10^{0.1L_{Ar}}-1}}}{\cosh^{-1}\Omega_S} \tag{4}$$

Where n is the order of the filter, L_{As} is the level of out-of-band rejection in the pulsation Ωs and L_{Ar} is the maximal amplitude of the undulation. Ωs is the frequency of rejection high, found by the equation of the transformation of frequency [7], whose cut-off frequency is Ωc=1 rad/s. The resonators in equivalent circuit are modeled by inductance and capacitance in series [7]:

$$L_{Si}\omega_0 = \frac{1}{C_{Si}\omega_0} = \frac{\Omega_C Z_0 g_i}{FBW} \quad 1 \leq i \leq n \tag{5}$$

Where FBW is the relative bandwidth of the filter, ω_0 is the center angular frequency and Z_0 is the source impedance. The coupling coefficients between resonators are provided by impedance inverters $K_{i,i+1}(0\leq i \leq n)$ [7].

$$K_{0,1} = \sqrt{\frac{Z_0 FBW \;\; \omega_0 L_{S1}}{\Omega_C g_0 g_1}} \tag{6}$$

$$K_{i,i+1} = \frac{FBW \;\; \omega_0}{\Omega_C}\sqrt{\frac{L_{Si} L_{S(i+1)}}{g_i g_{(i+1)}}} \quad 1 \leq i \leq n-1 \tag{7}$$

$$K_{n,n+1} = \sqrt{\frac{Z_{n+1} FBW \;\; \omega_0 L_{Sn}}{\Omega_C g_n g_{n+1}}} \tag{8}$$

On the other the waveguide filters are formed with resonator distributed elements interconnected by impedance inverters or admittance.

The distribution of the electric field in the SIW has characteristics of dispersal similar to the mode of the waveguide. The conception of filter SIW uses the same process the conception of a filter waveguide. The equivalent circuit of the band-pass filter SIW is presented by impedance inverter and phase shifts [8]. The impedance inverters $K_{i,i+1}(0\leq i \leq n)$ are given by the formulas in [9, 11]:

$$\frac{K_{0,1}}{Z_0} = \sqrt{\frac{\pi\,\omega_\lambda}{2\Omega_C g_0 g_1}} \tag{9}$$

$$\frac{K_{i,i+1}}{Z_0} = \frac{\pi\,\omega_\lambda}{2\Omega_C}\sqrt{\frac{1}{g_i g_{(i+1)}}} \quad 1 \leq i \leq n-1 \tag{10}$$

$$\frac{K_{n,n+1}}{Z_0} = \sqrt{\frac{\pi\,\omega_\lambda}{2\Omega_C g_n g_{n+1}}} \tag{11}$$

Where $g_i(0\leq i \leq n+1)$ Are the coefficients of Chebyshev, Ωc=1 rad/s is the cut-off frequency. ω_λ is the fractional bandwidth [9], defined by the guided wavelength λ_{g1}, λ_{g2} for cutoff frequencies f_1 low and f_2 high bandwidth, the guided wavelength λ_{g0} of the center frequency f_0:

$$\omega_\lambda = \frac{\lambda_{g1} - \lambda_{g2}}{\lambda_{g0}} \tag{12}$$

In hybrid networks inverters are a broadband [9], the equivalence relations with the inverters are represented by the following relationship 13, as in [11]:

$$\left|\frac{X_{i,i+1}}{Z_0}\right| = \frac{\dfrac{K_{i,i+1}}{Z_0}}{1-\left(\dfrac{K_{i,i+1}}{Z_0}\right)^2} \tag{13}$$

The phase shifts or the electrical lengths of the resonators are determined in [9]:

$$\phi_i = \pi + \frac{1}{2}\left[\theta_{i-1,i} + \theta_{i,i+1}\right] \quad 1 \leq i \leq n \tag{14}$$

With $\theta_{i-1,i} = -\tan^{-1}\left(\frac{2X_{i-1,i}}{Z_0}\right) \quad 1 \le i \le n$

The topologies of SIW have been extensively studied. For our study we used the topology with iris and topology with circular inductive post.

The SIW filter with circular inductive post is influenced by the lengths L_{SIWi} the cavities and by the diameter of circular post d_{SIWi} which delimit the cavities of the filter as shown in Fig. 4.

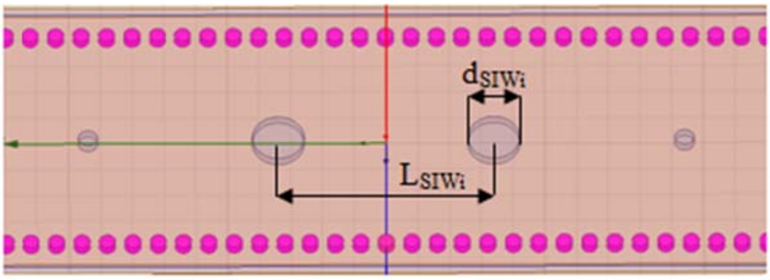


Fig. 4. SIW filter with circular inductive post

Circular post is represented by a diagram (or circuit) consisting of two equivalent capacitances X_S and self X_P as shown in Fig. 5.

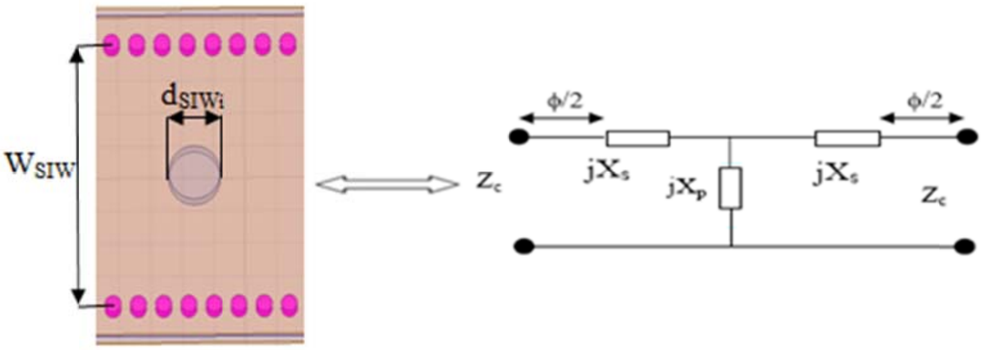


Fig. 5. Typical equivalent circuit for circular post

Where W_{SIW} Is the width of the waveguide, d_{SIWi} the diameter of circular post. The diameter of circular posts d_{SIWi} (i=0,1,2,….n) is determined by the equation 13 and the abacus of the estimated diameter in rectangular waveguide [10, 11]. The lengths L_{SIWi} (i=1,2,3,…n) the resonators are determined by the equation 15, as in [9] :

$$L_{SIWi} = \frac{\lambda_{g0}\phi_i}{2\pi} \quad 1 \le i \le n \tag{15}$$

Where ϕi (1≤ i ≤n) are the electrical lengths of the resonators.

The SIW filter with iris is influenced by the lengths L_{SIWi} (i=1,2,3…,n) the resonators and also by the coupling, That is an opening in the wall between two adjacent cavities. This type of opening is called iris (the widths W_{SIWi} (i=0,1,2…..n) the resonators) as shown in Fig. 6.

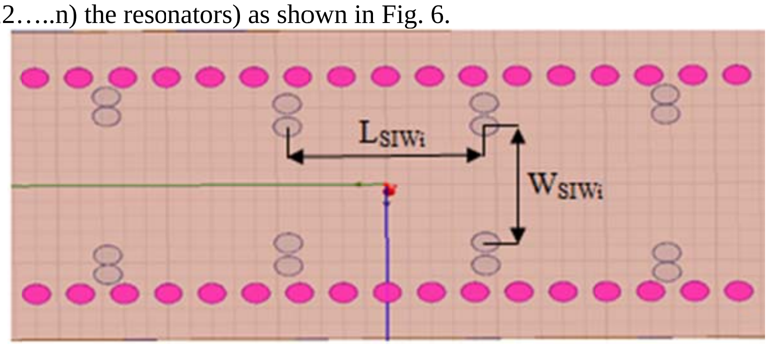


Fig. 6. SIW filter with iris

Iris is represented by a diagram (or circuit) consisting of two equivalent capacitances X_S and self X_P as shown in Fig. 7.

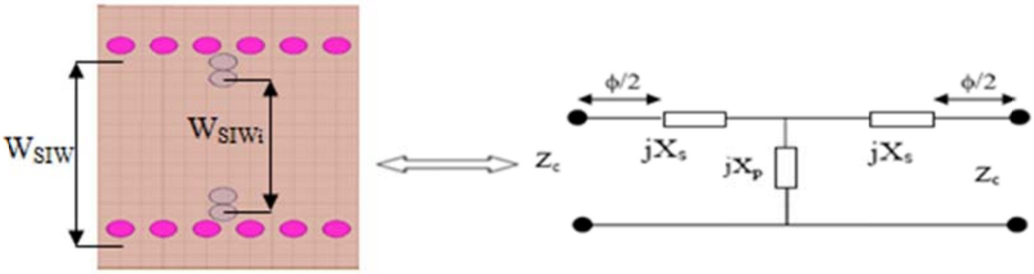


Fig. 7. Iris and his equivalent circuit

Where W_{SIW} is the width of SIW guide, W_{SIWi} is the width of the resonator. The lengths L_{SIWi} (i=1,2,3…,n) the cavities SIW inductive post filter are determined by the same method the SIW filter with circular inductive post. The widths W_{SIWi} (i=0,1,2…..n) of the resonators in SIW technology are determined by the equation 13 and the abacus of the estimated width in rectangular waveguide [10].

IV. Results

A. SIW Filter with Circular Inductive Post in the Band [33-50] GHz

This filter is designed with a RT/Duroid 5880 substrate the relative permittivity ε_r=2.2 and the height h = 0.254 mm. we take the diameter of the metallic via D = 0.25 mm and the period of the vias P = 0.4 mm.

The standard guide of the band [33-50] GHz having the dimensions a=5.7 mm and b=2.85 mm, for the cutoff frequency of TE_{10} Mode fc) 10 =26.3 GHz and according to the relations 1 and 3 we deduct the effective width W_{eff} =3.84 mm and the distance between the rows of the centres of via is W_{SIW} =4 mm.

Now we found the dimensions of the SIW structure, a microstrip transition is used to interconnect SIW to the planar transmission lines. She is used to match the impedance between a 50 Ω microstrip line and the SIW. The 50 Ω microstrip line, in which the dominant mode is quasi-TEM, can excite well the dominant mode TE_{10} of the SIW, as their electric field distributions are approximate in the profile of the structure.

The parameters (the width W_M) of the microstrip line and (the width W_T and the length L_T) the transition determined from several formulas given in [4, 6].
The microstrip line: W_M=0.63 mm
The dimensions of transition: W_T =1.5 mm and L_T =4 mm.
The structure of the transition is produced in forms tapered as shown in Fig. 8.

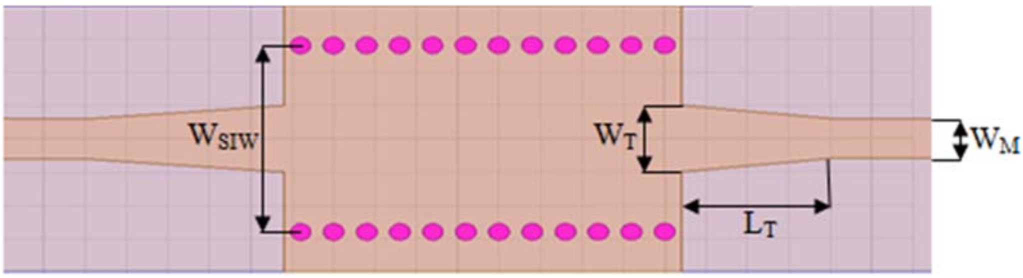


Fig. 8. SIW with two tapered transitions

This structure is simulated by using HFSS. The simulated S-parameters of SIW with two tapered transitions in the frequency band 33 – 50 GHz are shown in Fig. 9.

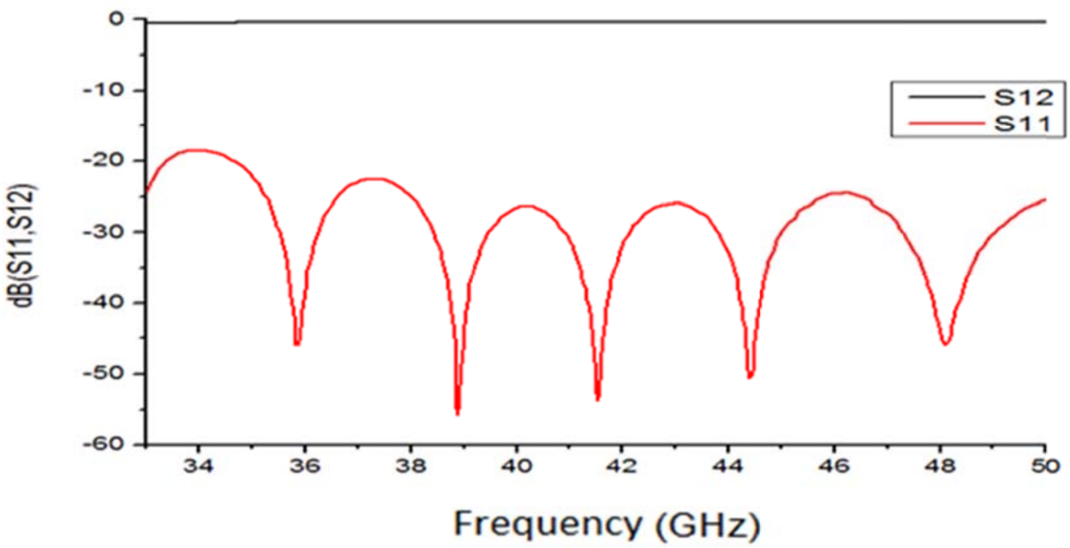


Fig. 9. Frequency response of SIW with two tapered transitions

The results illustrated in Fig. 9, indicate that the reflection coefficient S11 remains below-15dB on the entire band [33-50] GHz and the transmission coefficient S12 is around -0.5 dB across the entire band.

Before passing to the design of SIW filter circular inductive post in the band [33-50] GHz, we studied their equivalent circuit [7], by using software 2D simulation (ADS). This filter has a centre frequency f_0= 41.7 GHz, the absolute bandwidth 1.5 GHz and the relative bandwidth FBW = 3.5 %. The insertion loss around 41.7 GHz is approximately -0.4 dB, the return loss is better than-15 dB between 41.1 GHz and 42.4 GHz.

By exploiting the equation 4, we deduct a 3[rd] order filter. The elements of resonators and the impedance inverters are calculated by equations 5, 6, 7 and 8:

L_{s1}=68.6 pH, C_{s1}=0.21 pF, L_{s2}=105.8 pH, C_{s2}=0.13pF, L_{s3}=68.6 pH, C_{s3}=0.21 pF

$K_{0,1}$=0.999 ,$K_{1,2}$=0.999 ,$K_{2,3}$=0.999

Fig. 10 shows the equivalent circuit of this filter.

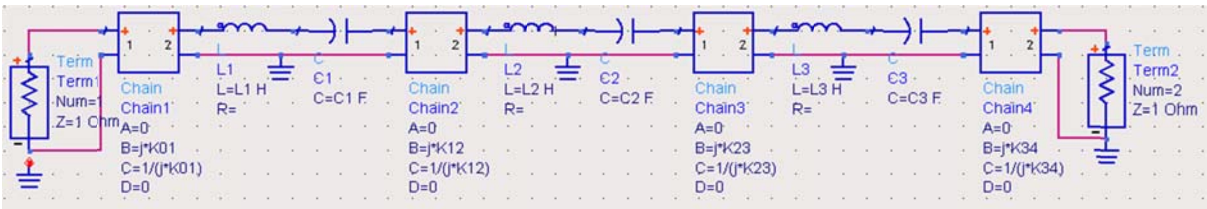


Fig. 10. Circuit model of microwave filter in ADS

Fig. 11 illustrated the reflection coefficient S11 and the transmission coefficient S12 of this filter in the band [33-50] GHz.

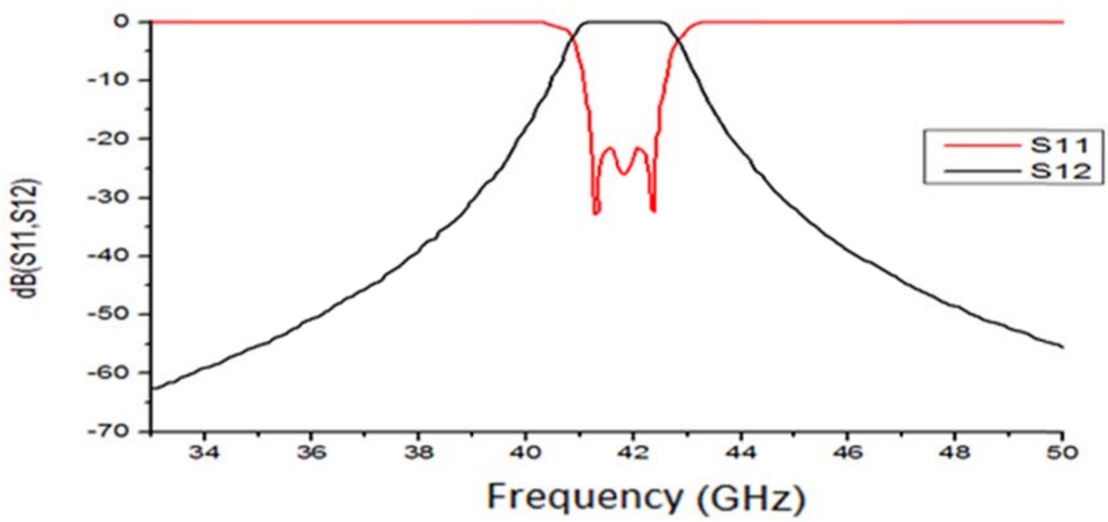


Fig. 11. Frequency response of microwave filter

The results illustrated in Fig. 11, show the filter has a centre frequency f_0= 41.8 GHz, the absolute bandwidth 1.7 GHz and the relative bandwidth FBW= 4 %. The return loss is better than-15 between 41.1 GHz and 42.4 GHz. It can be seen that the filter respects well the tender specifications.

The conception of SIW filter circular inductive post in the band [33-50] GHz, using HFSS and RT/Duroid 5880 substrate for comparing with the results in [12]. We obtained the SIW filter a 3rd order; the cavities of the filter using inductive post are shown in Fig. 12.

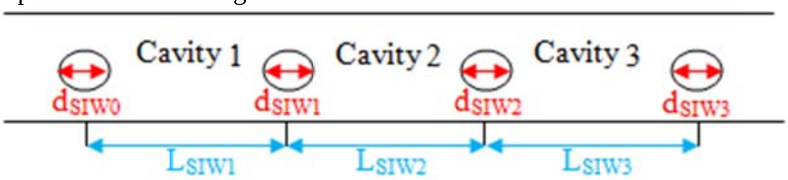


Fig. 12. Topology SIW filter with circular inductive post

Where d_{SIWi} (i=0,1,2,3) are the diameter of circular posts and L_{SIWi} (i=1,2,3) are the lengths of the resonators. Using the method of the abacus [11] and the equations 15 and 14, we find:

d_{SIW0}=d_{SIW3}=0.33 mm and d_{SIW1}=d_{SIW2}=0.94 mm

L_{SIW1}=L_{SIW3}=2.8 mm and L_{SIW2}=3 mm

These results constitute the initial parameters, following by an optimization using the HFSS. The optimal parameters are:

L_{SIW1}=L_{SIW3}=3 mm and L_{SIW2}=3.4 mm

d_{SIW0}=d_{SIW3}=0.3 mm and d_{SIW1}=d_{SIW2}=0.82 mm

W_T=1.5 mm and L_T=4 mm

D = 0.25 mm, P = 0.4 mm, W_{SIW} = 4 mm and W_M =3.84 mm.

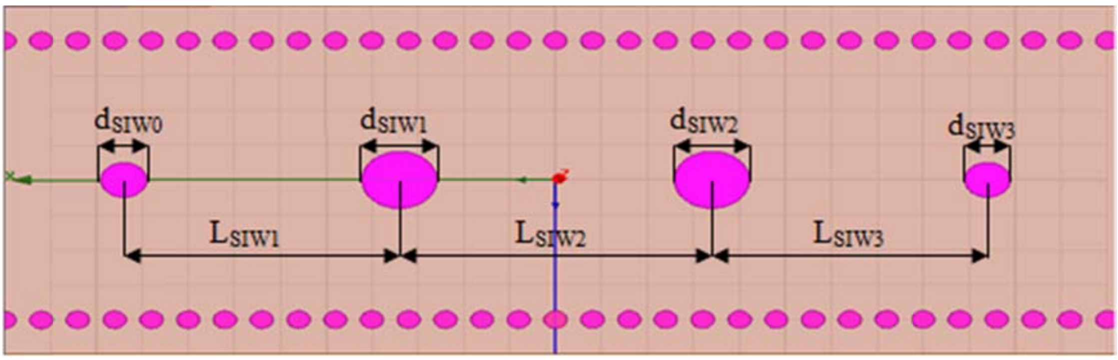
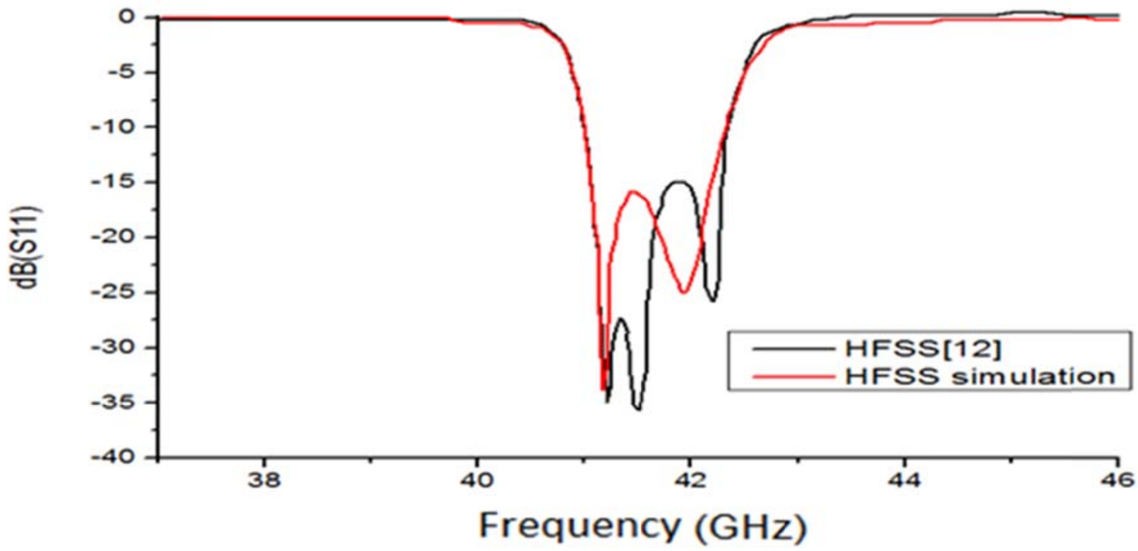
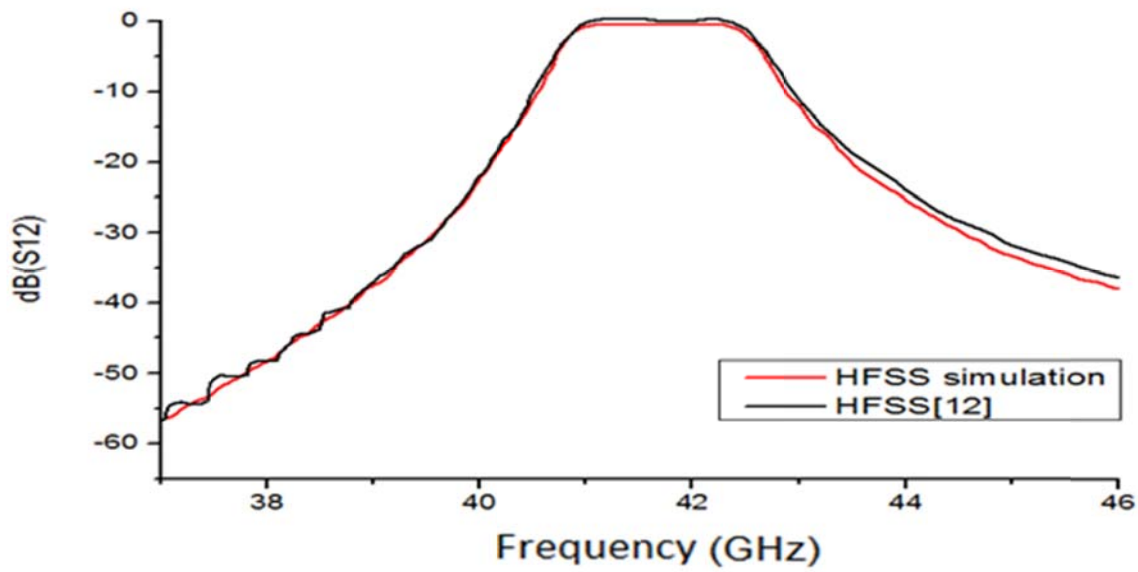


Fig. 13. SIW filter with stepped transition using inductive post

Fig. 14 illustrated the reflection coefficient S11 and the transmission coefficient S12 of the SIW filter with circular inductive post and also the results in [12].



(a)



(b)

Fig. 14. Frequency responses of SIW filter inductive post. (a) Reflection coefficient S11 as a function of frequency. (b) Transmission coefficient S12 as a function of frequency (—— HFSS simulation —— HFSS [12])

The result of the simulation HFSS shows that the centre frequency f_0= 41.7 GHz, the absolute bandwidth 1.5 GHz and the relative bandwidth FBW= 3.5 %. The insertion loss around 41.8 GHz is approximately -0.4 dB, the return loss is better than-15 dB between 41.1 GHz and 42.4 GHz. The results obtained by HFSS simulation are in good agreement with the results in [12] (HFSS [12]).

B. SIW Filter with Inductive Post-Wall Irises in the Band [50-75] GHz

Title For this filter we used the Neltec NY9217 (IM) substrate the relative permittivity ε_r=2.17 and the height h = 0.2 mm. we take the diameter of the metallic via D = 0.25 mm and the period of the vias P = 0.4 mm.

Generally the standard guide of this band [50-75] GHz having the dimensions a=3.7592 mm and b=1.8796 mm and according to the relations 1 and 3 we deduct: W_{eff} =2.58 mm and W_{SIW} =2.8 mm.

However, for adapted the SIW guide we followed the same approach the conception of the tapered microstrip line transition [4-6], we found:

W_M=0.63 mm, W_T =1 mm and L_T =1.8 mm

Fig. 15 illustrated the reflection coefficient S11 and the transmission coefficient S12 of SIW with two tapered transitions in the band [50-75] GHz.

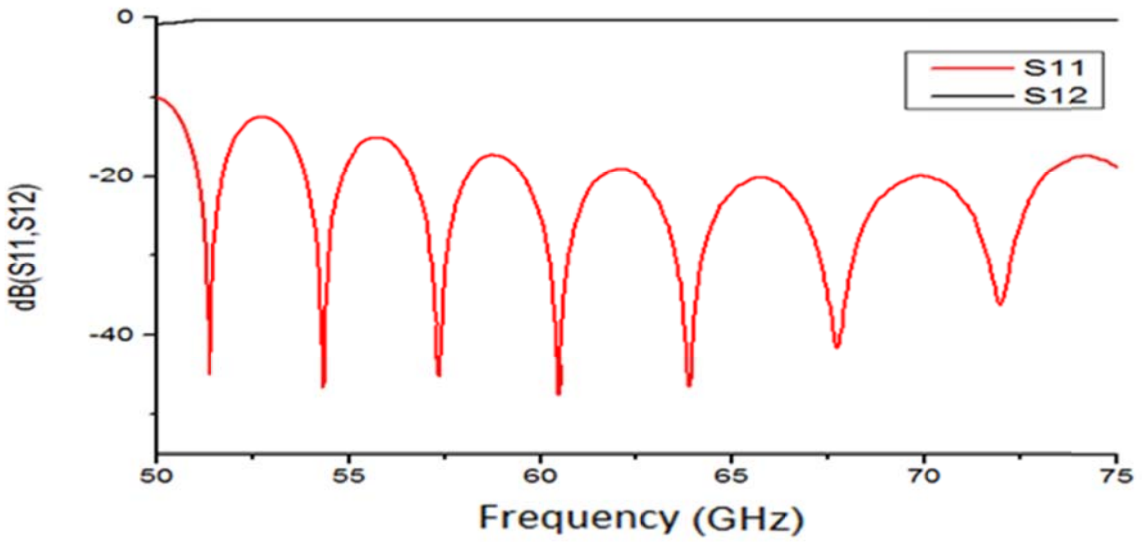


Fig. 15. Frequency response of SIW with two tapered transitions

The results illustrated in Fig. 15, indicate that the reflection coefficient S11 remains below-15dB over 90 % of the band [50-75] GHz and the transmission coefficient S12 is around -0.7 dB across the entire band.

However, for the design of SIW filter iris in the V-band we proposed the following template:

A centre frequency f_0= 62 GHz, the absolute bandwidth 12 GHz and the relative bandwidth FBW = 19 %. The insertion loss around 62 GHz is approximately -0.35 dB, the return loss is better than -15 dB between 60 GHz and 66.3 GHz.

For the theoretical study of the equivalent circuit of this filter by using software 2D simulation (ADS), we exploited the relations 4, 5, 6, 7 and 8, we deduct a 3rd order filter and that the elements of resonators and the impedance inverters are:

L_{s1}=7.4 pH, C_{s1}=0.77 pF, L_{s2}=13 pH, C_{s2}=0.5 pF, L_{s3}=8.4 pH, C_{s3}=0.77 pF

$K_{0,1}$=0.998 ,$K_{1,2}$=1 ,$K_{2,3}$=0.998.

After the simulation, we found the ideal frequency response of the circuit on the band [50-75] GHz as shown in Fig. 16.

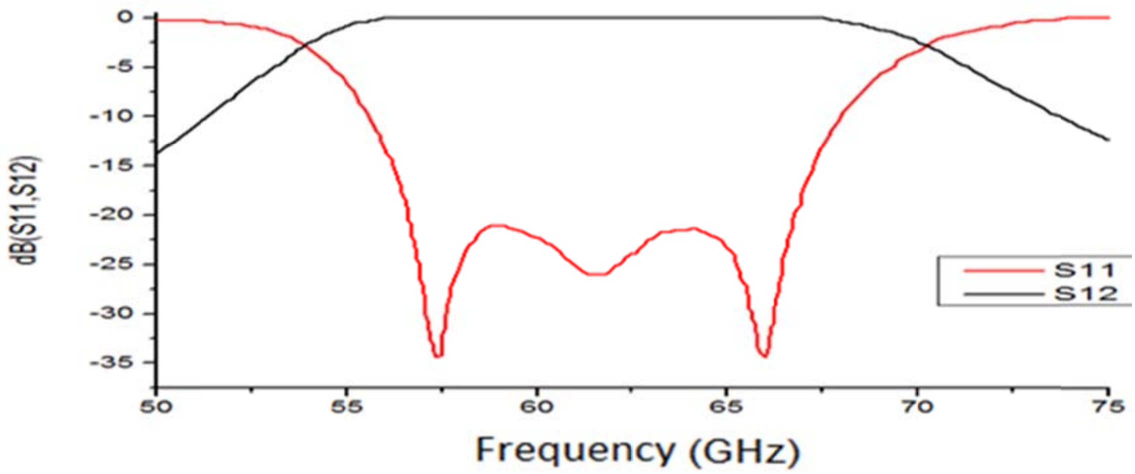


Fig. 16. Frequency response of microwave filter

The results illustrated in Fig. 16, show the filter has a centre frequency f_0= 62 GHz, the absolute bandwidth 16.2 GHz and the relative bandwidth FBW= 26 %. The return loss is better than-15 between 56.3 GHz and 67.3 GHz. It can be seen that the filter respects well the tender specifications.

After the study of equivalent circuit of SIW filter iris in the band [50-75] GHz, we are going to design, using Neltec NY9217 (IM) substrate for comparing with the results in [9]. We obtained the SIW filter a 3rd order; the cavities of the filter using inductive post-wall irises are shown in Fig. 17.

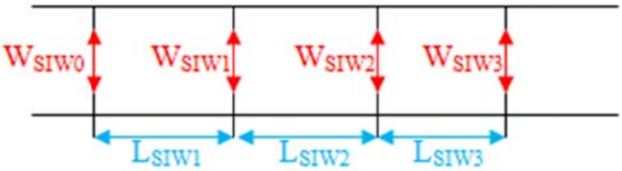


Fig. 17. Topology SIW filter with iris

Where W_{SIWi} (i=0,1,2,3,) Are the widths of the resonators and L_{SIWi} (i=1,2,3) are the lengths of the resonators. Using the method of the abacus [10, 11] and the equations 15 and 14, we find these results which are going to be optimized by HFSS. The final dimensions of the structure are:

$L_{SIW1}=L_{SIW3}=1.65$ mm and $L_{SIW2}=1.8$ mm
$W_{SIW0}=W_{SIW3}=1.91$ mm and $W_{SIW1}=W_{SIW2}=1.51$ mm
$W_T=1$ mm and $L_T=1.8$ mm
D = 0.25 mm, P = 0.4 mm, W_{SIW} = 2.8 mm and W_M =0.63 mm

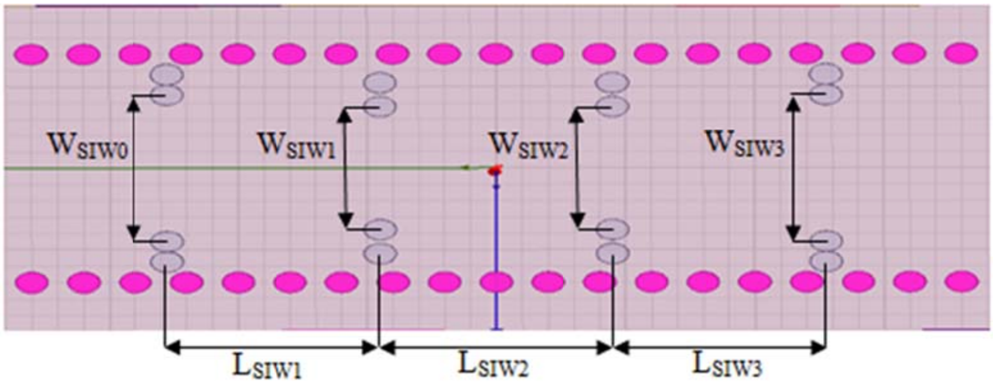
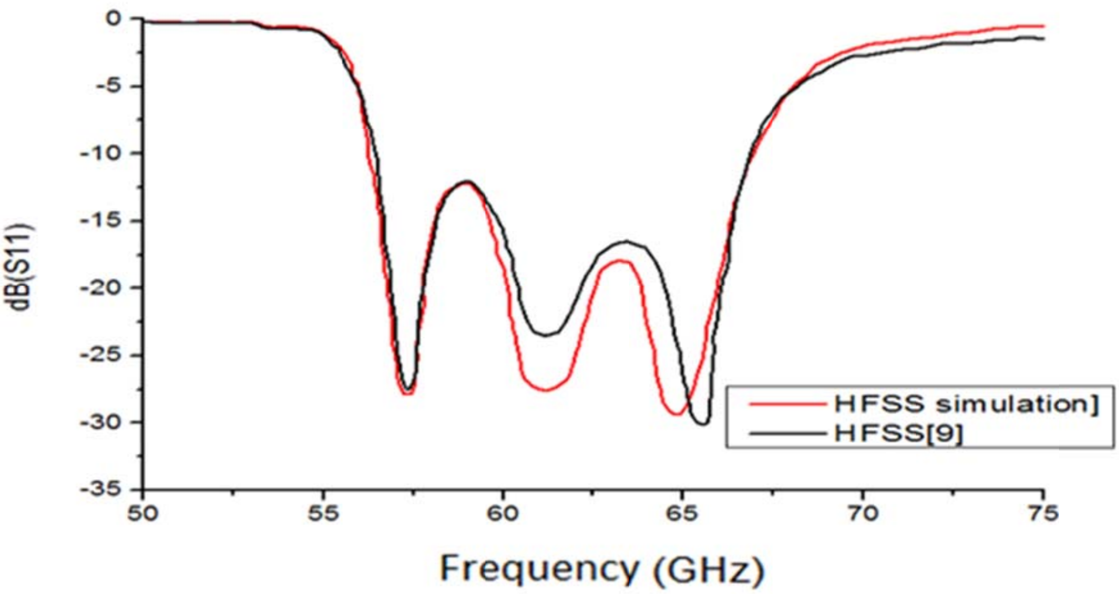
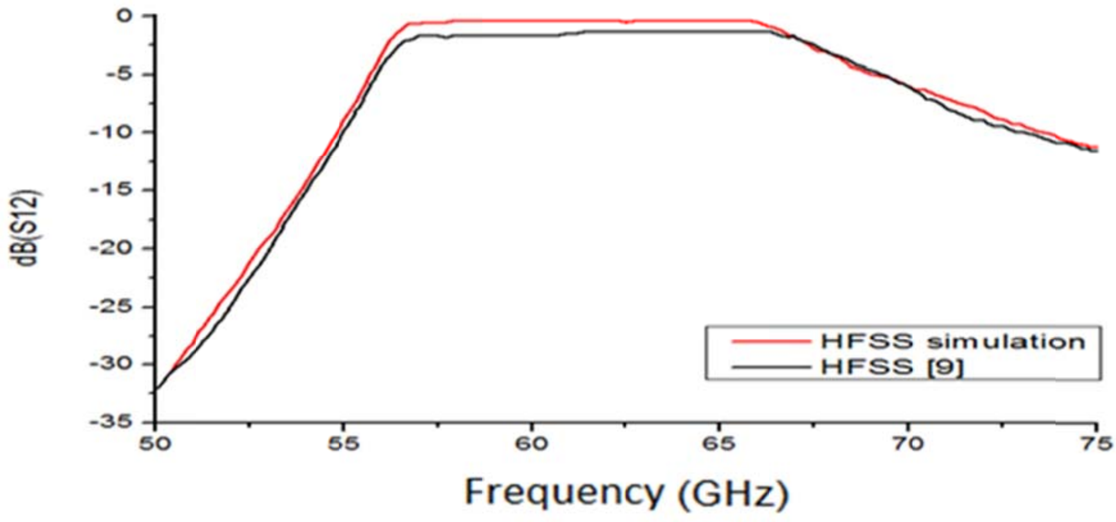


Fig. 18. SIW filter with stepped transition using post-wall irises

Fig. 19 illustrated the reflection coefficient S11 and the transmission coefficient S12 of the SIW filter with iris and also the results in [9].



(a)



(b)

Fig. 19. Frequency response of SIW filter iris. (a) Reflection coefficient S11 as a function of frequency. (b) Transmission coefficient S12 as a function of frequency (——HFSS simulation ——HFSS [9])

The result of the simulation HFSS shows that the centre frequency f_0= 62 GHz, the absolute bandwidth 12 GHz and the relative bandwidth FBW= 19 %. The insertion loss around 62 GHz is approximately -0.35 dB, the return loss is better than-15 dB between 60 GHz and 66.3 GHz. The results obtained by HFSS simulation are in good agreement with the results in [9] (HFSS [9]).

V. Conclusion

In this work, we realized two SIW filters are a 3rd degree, the first SIW filter in band [33-50] GHz based on the topology with circular inductive post, he showed the insertion loss around 41.7 GHz is approximately -0.4 dB and the relative bandwidth 3.5%, the return loss is better than-15 dB between 41.1 GHz and 42.4 GHz. The second SIW filter in band [50-75] GHz based on the topology with iris, presented the insertion loss around 62 GHz is approximately -0.35 dB and the relative bandwidth 19%, the return loss is better than-15 dB between 60 GHz and 66.3 GHz.

The proposed filters are applied in the inter-satellite communications, he can be directly integrated with other circuits and it meets the constraints of cost cutting and simplicity of manufacturing imposed by market developments microwave components.

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