

Conception and Optimization of X Band SIW Band Pass Filter

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Abstract: In this paper, we present methods to design a bandpass filter based on an electronic circuit, a passage was made to design a filter based on a waveguide fill air and finally, based on a substrate integrated waveguide SIW. A fourth-order example, in band X, centered on 8.9 GHz with a bandwidth of 400 MHz, is modeled, simulated and optimized, by three program ADS, HFSS and CST. Very good results were obtained.

1 INTRODUCTION

Newly, a hybrid structure between the waveguides and the microstriple line has been developed, this structure called substrate integrated waveguide (SIW).

The air in the guide is replaced by a dielectric material (substrate) and the side walls by metal Vias, while preserving the upper and lower metallization.

The design of passive microwave structures and in particular filters has an important role in the manufacture of the various devices (Damou, 2018).

Bandpass filters are one of the essential components in multiple telecommunication systems, for that many studies and researches are done to improve its performance and to miniaturize its sizes.

In this work, we interest in designing and miniaturize a bandpass filter in the band X.

2 ANALYSIS OF INTEGRATED WAVEGUIDE

A waveguide is a metal tube filled with air, his voluminous structure make it difficult to integrate in the telecommunication means, which become more and more thin and lightweight (Adabi & Tayaran, 2008).

For solving these problems, the guide is filled by a substrate of permittivity ϵ_r , regarding, the side

The dimensions of SIW can calculated by these two formulas (Grine, 2018):

walls have been replaced by metal vias of diameter d .

This novel structure is called SIW (substrate integrated waveguide).

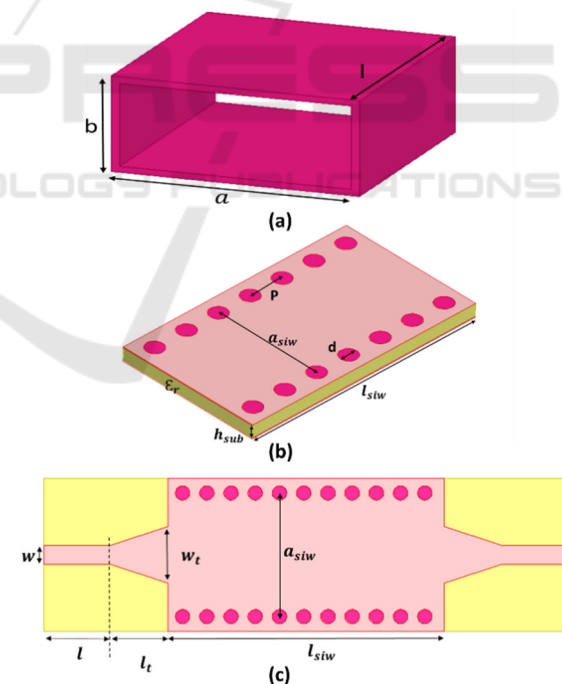


Figure 1: (a) rectangular waveguide (b) SIW (c) SIW with impedance adapter

$$a_{siw} = \frac{a}{\sqrt{\epsilon_r}} + \frac{d^2}{0.95 p} \quad (1)$$

$$l_{siw} = \frac{l}{\sqrt{\epsilon_r}} + \frac{d^2}{0.95 p} \quad (2)$$

The transition called taper, was used to realize the impedance matching between the SIW structure and that of the microstrip line (feeding line), its initial dimensions are obtained by the use of the formulas given in (Caleffo, 2015) and by HFSS (High Frequency Structure Simulator v13.0) or CST (Microwave Studio Software v2014.00) we can optimize them to get a good adaptation.

3 THE DESIGN OF BANDPASS FILTER

In this paper, a study was done to design a bandpass filter, with three different components: electronic circuit, waveguide and SIW structure.

Therefore, steps were followed to calculate the different parameters of each structure.

3.1 Electronic Circuit Bandpass Filter

The bandpass filter is a filter that lets passes only the frequencies between two cutoff frequencies (low cutoff frequency f_1 and a high cutoff frequency f_2).

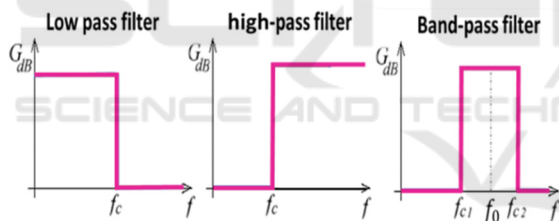


Figure 2: Gabarit of Low pass filter, high pass filter and band-pass filter

$$f_0 = \frac{f_1 + f_2}{2} \quad (3)$$

Band Width

$$BW = f_2 - f_1 \quad (4)$$

Relative Band Width

$$FBW = \frac{f_2 - f_1}{f_0} \quad (5)$$

A pass-band filter is the combination of low-pass filter (which lets pass only the frequencies lower than a desired frequency) and its opposite (high-pass filter) (Lei et al, 2012).

For that, a transfer function has been applied.

In our case, we used a Chebyshev Low pass Prototype Filters.

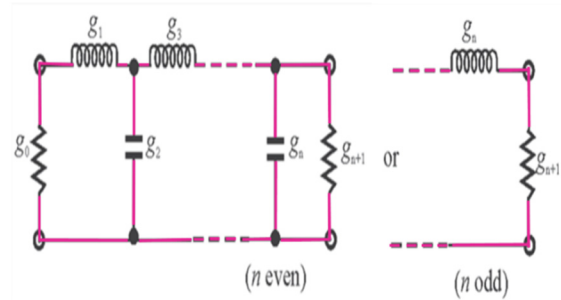


Figure 3: Chebyshev Low pass prototype filters

The equations to calculate the element values for Chebyshev low pass prototype filters are mentioned below

$$g_0 = 1 \quad (6)$$

$$g_1 = \frac{2}{\gamma} \sin\left(\frac{\pi}{2n}\right) \quad (7)$$

$$g_i = \frac{1}{g_{i-1}} \frac{4 \sin\left[\frac{(2i-1)\pi}{2n}\right] \sin\left[\frac{(2i-3)\pi}{2n}\right]}{\gamma^2 + \sin^2\left[\frac{(i-1)\pi}{n}\right]} \quad (8)$$

i=2,3,..n

$$g_{n+1} = \begin{cases} 1 & \text{for } n \text{ odd} \\ \coth^2 \frac{\beta}{4} & \text{for } n \text{ even} \end{cases} \quad (9)$$

$$\gamma = \sinh\left(\frac{\beta}{2n}\right) \quad (10)$$

$$\beta = \ln \left[\cotgh \left(\frac{L_{ar}}{17.37} \right) \right] \quad (11)$$

With L_{ar} : the passband ripple (dB) (Hong, 2011).

Once, the element values g are calculated, we can determine the equivalent electronic circuit values by calculate:

- the coupling matrix $[M]$ (Tubail1 & Skaik, 2017)

$$M_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \quad i=1 \text{ to } n-1 \quad (12)$$

- The external quality factor (Shang et al, 2014)

$$Q_{e1} = \frac{g_0 g_1}{FBW} \quad Q_{en} = \frac{g_n g_{n+1}}{FBW} \quad (13)$$

- Finally, the values of the LC elements

$$L_{eq} = \frac{Z}{\omega_0 Q_0} \times 10^9 \text{ (nH)} \quad (14)$$

$$C_{eq} = \frac{Q_0}{\omega_0 Z} \times 10^{12} \text{ (pF)} \quad (15)$$

3.2 Bandpass Filter with Inductive Iris

For adding a filter function to a waveguide, we need to create a discontinuity or a modification inside it. This discontinuity can be a change in its geometry, its direction of propagation or one of its physical parameters (permittivity, permeability).

In our case, two metal plates are inserted in the waveguide (parallel to the electric field E).

These two plates are symmetrical according to the size of the waveguide (Vanhoenacker & Vorst, 1996).

The electrical diagram equivalent to this discontinuity is an inductive susceptance, (Damou, 2018) as shown in the figure 4.

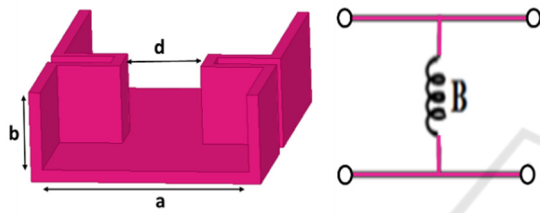


Figure 4: Iris waveguide bandpass filter and his inductive susceptance equivalent.

However, to calculate the different parameters of bandpass filter based on the symmetrical inductive irises, these steps must be followed:

- Calculate the reactance of the iris $x_{i,i+1}$ and $x_{i-1,i}$

$$x_{i,i+1} = \frac{L}{\sqrt{g_i g_{i+1}}} / \left(1 - \frac{L^2}{g_i g_{i+1}}\right) \quad (16)$$

$i=0, 1 \dots n$

$$x_{i-1,i} = \frac{a}{\lambda_{g0}} \left(\frac{1}{s_i^2} - 1 - \frac{(1-s_i^2)^2}{1-\delta_3 s_i^6} \right) \quad (19)$$

$$(3\delta_3 + 5\delta_5 \frac{(2s_i^2-1+\delta_3 s_i^6(s_i^2-2))^2}{(1-\delta_3 s_i^6)(1-\delta_5 s_i^{10})-15\delta_5 s_i^6(1-s_i^2)^2})$$

With

$$L = \pi \frac{\lambda_{g1} - \lambda_{g2}}{\lambda_{g1} + \lambda_{g2}} \quad (17)$$

$$\lambda_{g_i} = \frac{2a}{\sqrt{\left(\frac{2af_i}{c}\right)^2 - 1}} \quad i=0,1,2 \quad (18)$$

λ_{g_i} The corresponding guided wavelengths
And

$$\delta_m = 1 - \sqrt{1 - \left(\frac{2a}{m\lambda_0}\right)^2} \quad m=3,5 \quad (20)$$

- Calculate electrical length between the irises ϕ_i (radians)

$$\phi_i = \pi - \frac{\tan^{-1}(2x_{i-1,i}) + \tan^{-1}(2x_{i,i+1})}{2} \quad (21)$$

$i=1, 2, \dots, n$

- Finally, the length l_i between two consecutive irises, and the width d_i between two opposite irises (Zhai et al, 2008).

$$l_i = \frac{\lambda_{g0}}{2\pi} \phi_i \quad i=1, 2, \dots, n \quad (22)$$

$$d_i = \frac{2a}{\pi} \sin^{-1}(S_i) \quad i=1, 2, \dots, n+1 \quad (23)$$

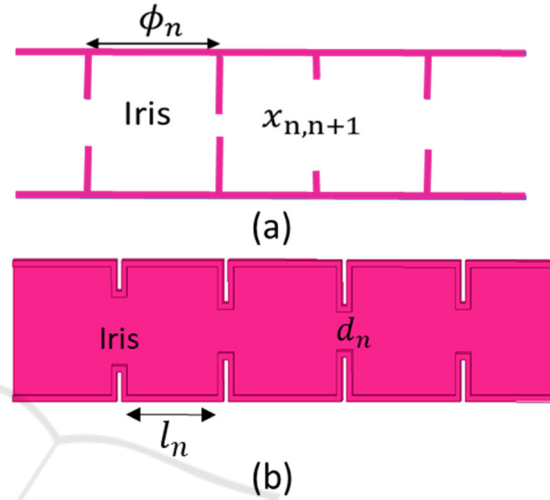


Figure 5: the parameters of a) transmission line b) iris waveguide bandpass filter

Once, the initial dimensions of the waveguide are calculated, it is necessary to optimize them for respecting the conditions of our specifications.

This operation is made by simulators like HFSS and CST.

The dimensions of the SIW cavities are connected to that of the waveguide such that:

$$l_{siw_i} = \frac{l_i}{\sqrt{\epsilon_r}} + \frac{d^2}{0.95 p} \quad (1)$$

$$d_{siw_i} = \frac{d_i}{\sqrt{\epsilon_r}} + \frac{d^2}{0.95 p} \quad (2)$$

4 DESIGN EXAMPLE

To verify the method given earlier, an example in the band X [8, 12] GHz was proposed.

Moreover, for facilitating the calculations, we create under Matlab (Matrix Laboratory v R2014a) a program that contains the previous equations.

Just enter the data specified for our filter, this gives us the parameters needed to design it by electronic circuits and a rectangular waveguide.

For that, and to organize our work well, we have set this specification:

- Filter type: Chebyshev, order 4.
- The cutoff frequency: $f_{c10} = 6.557$ GHz
- The center frequency: $f_0 = 8.9$ GHz.
- Ripple: $L_{ar} = 0.04321$ dB.
- Bandwidth: $BW = 0.4$ GHz.
- Relative bandwidth: $FBW = 4.494\%$.

We start with designing the electronic circuit, therefore, the parameters obtained by the Matlab program are:

- the g values
 $gi = [1 \ 0.9314 \ 1.292 \ 1.5775 \ 0.7628 \ 1.221]$
- the coupling matrix

$$M = \begin{bmatrix} 0 & -0,0466 & 0 & 0 & 0 & 0 \\ -0,0466 & 0 & 0,0410 & 0 & 0 & 0 \\ 0 & 0,0410 & 0 & -0,0315 & 0 & 0 \\ 0 & 0 & -0,0315 & 0 & 0,0410 & 0 \\ 0 & 0 & 0 & 0,0410 & 0 & -0,0466 \\ 0 & 0 & 0 & 0 & -0,0466 & 0 \end{bmatrix}$$

- The external quality factor
 $Q_{e1} = 20.7236$
- LC elements of resonators
 $l_{eq} = 0.0431$ nH
 $C_{eq} = 7.4118$ pF

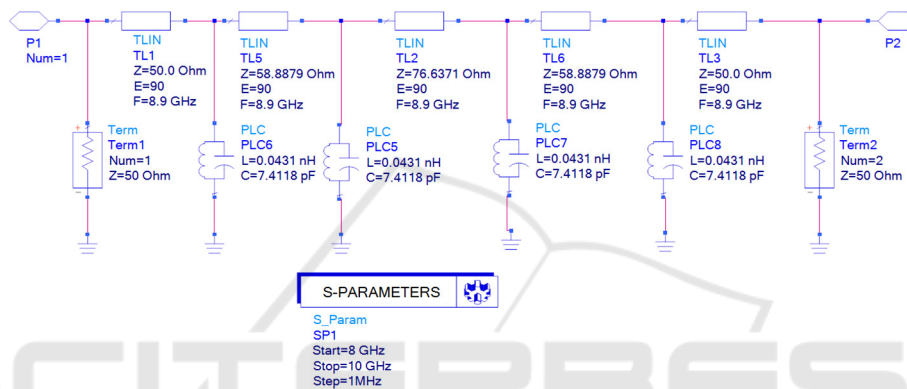


Figure 6: the bandpass electrical circuit with ADS

After extracting these parameters, they are used in conceiving the electronic circuit.

This operation is made under ADS (Advanced Design System v2016.01) software which is specialized in the design of electronic circuits in particular, circuits for RF applications .figure(6)

Then, we pass to design the waveguide bandpass filter.

In this case, the chosen waveguide has a rectangular section with $a=22.86$ mm and $b=10.16$ mm.

The equations (16) to (23) was used to determine the reactances, the electrical lengths, and finally the different parameters of our bandpass filter (d_i and l_i) figure 7.

These initial dimensions are simulated and optimized by HFSS and CST. The table 1 illustrates the final dimensions (the values are in millimeters).

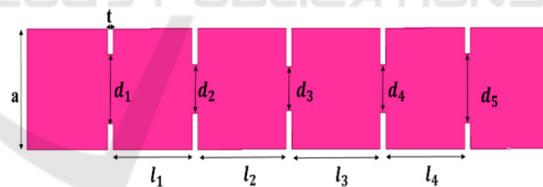


Figure 7: the different parameters for fourth order bandpass filter

Table 1: the dimensions of bandpass waveguide filter

l_1	l_2	l_3	l_4	t
20.1	22.5	22.5	20.1	1
d_1	d_2	d_3	d_4	d_5
13.1	9.1	8.3	9.1	13.1

Now, we pass to conceive and simulate SIW structure.

The substrate used in the design is Rogers RO3006, this substrate is known in microwave applications for its electrical and mechanical stability and its competitive price.

($h_{siw}=0.5$ mm, $\epsilon_r=6.15$ and $\tan(\delta)=0.0025$) are respectively (the height, the permittivity and loss tangent) of this substrate

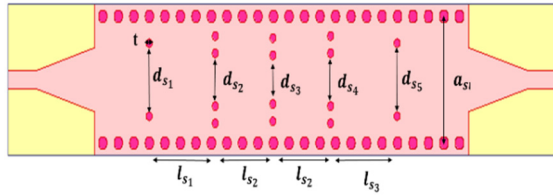


Figure 8: the different parameters for fourth order bandpass filter

By employing the equations (1, 2) and (24, 25), It is possible to calculate the different initial dimensions of the SIW bandpass filter.

Table 2: the dimensions of bandpass SIW filter

a_{siw}	D	P	w_t	l_t
10.14	1	1.8	4.27	10
l_{s_1}	l_{s_2}	l_{s_3}	l_{s_4}	T
7.66	8.7	8.7	7.66	0.49
d_{s_1}	d_{s_2}	d_{s_3}	d_{s_4}	d_{s_5}
4.95	3.22	2.89	3.22	4.95

The table 2 illustrates the final values (in millimeters) of SIW structure (after the optimization by CST and HFSS)

5 RESULTS AND DISCUSSION

In this work, we design a Chebyshev bandpass filter of the order 4 in the X band. Therefore, we set objectives to be achieved.

The initial dimensions obtained are used to design a waveguide with four symmetrical iris (figure 7), the results are in figure 9.

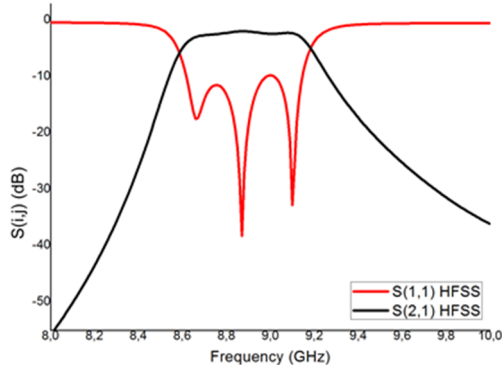


Figure 9: Frequency response of the waveguide initial dimensions (HFSS)

The frequency response shows a filter close to our desired filter, but it is necessary to optimize it by the HFSS or the CST.

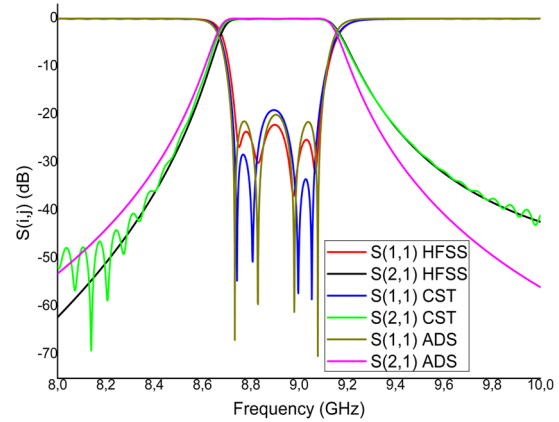


Figure 10: Comparison of the symmetric iris waveguide bandpass filter responses (HFSS, CST) and the circuit results (ADS)

Figure 10 indicates a comparison of symmetric iris waveguide (HFSS, CST) and circuit (ADS) responses.

The results show that our specifications are respected (the center frequency $f_0=8.9$ GHz, the bandwidth $BW=0.4$ GHz).

Noted that the S11 for the three responses (HFSS, CST and ADS) at the passband have three ripples that means four peaks corresponding to the order ($n = 4$) and the reflection levels is less than -20 dB.

Now, we pass to the SIW structure and by using the optimized dimensions of Table 1, we could stimulate it on HFSS and validated on CST.

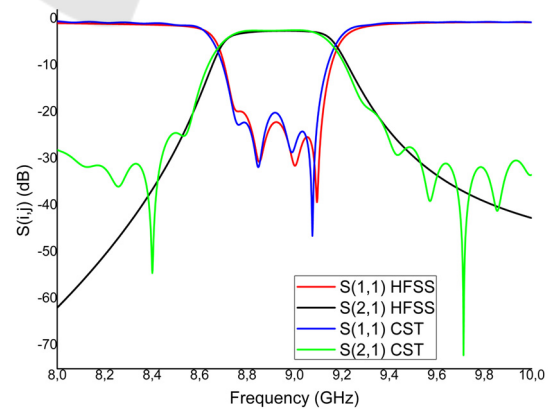


Figure 11: Comparison of the symmetric iris SIW bandpass filter responses (HFSS, CST)

It is very clear that the responses are similar and confused, and they meet our specifications in terms of center frequency ($f_0=8.9$), of the bandwidth (BW=0.4 GHz) and even the type of filtering chosen (Chebyshev) and its order ($n=4$).

Moreover, the reflection losses in the bandwidth are below than -20db.

HFSS and CST allow us to map the electromagnetic field of the structures analyzed, that is meant, seeing the distribution of the wave TE₁₀ inside them.

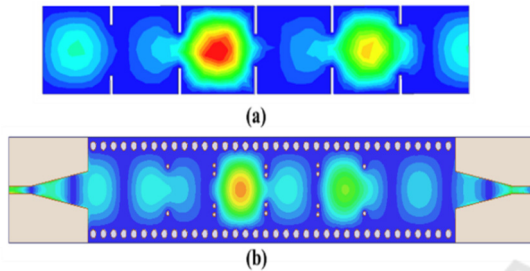


Figure 12: electric fields of the TE₁₀ mode at $f_0 = 8.9$ GHz of a) waveguide bandpass filter b) SIW bandpass filter

Figure 12 shows the identical of the electromagnetic field distribution in the waveguide and the SIW structure at the center frequency.

For the moment, we designed and simulated two bandpass filter structures, we analyzed its results, we found that both of them are respected our specifications.

So, what makes one of them better than the other?

To answer this question it is necessary to observe Table 3, which contains the total dimensions of each structure.

Table 3: dimensions of each structure

	a (mm)	L (mm)	H (mm)
Waveguide $\epsilon_r=1$	22.86	131.28	10.16
SIW $\epsilon_r=6.15$	10.14	63.31	0.664
Reduction %	55.65%	51.77%	93.46%

According to table 3, there is a big difference between these two structures in terms of dimensions, such that, the length and width of the SIW structure are reduced by half, without forgetting the height which reduced by 93.46%.

Therefore, the dimension factor has a big importance in the fabrication of the different devices.

Scientists are currently trying to minimize the size of components and make them easy to manufacture and integrate with planar circuits, at a low cost.

After these studies, we can say that the SIW structure can meet these requirements.

6 CONCLUSION

In this work, we designed a pass band filter in the band X by adding inductive iris to two structures the first is a guide filled with air, the second is a guide filled with substrate.

As a result, the SIW structure allows us to miniaturize our filter more than half.

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