Design of Ka-Band Planar Pass-Band Filter of Fifth Order Based on SIW Technology

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***Abstract*—This paper proposes a fifth order wide band pass filter, based on the technology of Substrate Integrated Waveguide SIW, endowed by inductive iris and manufactured by using the substrate Polyflon Cuflon (tm), that made him extra planar component with low loss. Where the ideal return loss "RL" reaches almost -40dB at the frequency 32.54 GHz. This filter has been designed in order to resonate in the millimeter waves, especially Ka band, with wide band BW of 7GHz. This design has been developed and simulated using EM software "HFSS".**

Keywords—SIW Cavity, Millimeter waves, BP filter, Ka-band.

I. INTRODUCTION

The domain of telecommunication systems have a great interest from researchers in the world wide, because this domain affects almost daily strategic sectors as well as military, education and scientific researchers, health and effectively the spatial communications and networks.

Recently, in order to have a lot of objects connected at the same time with the lowest delay of execution and high rate of information's transmission, it is necessary to develop components working in high frequencies (HF) [1]. These structures are considered in lower wavelengths like the millimeters waves, which have wavelength from 1 mm to 10 mm, and occupy frequencies range from 30 GHz to 300 GHz. They have been unscrewed on several bands as Ka-band within the range from 26.5 GHz to 40 GHz [1-2]. In order to have good performances, the researchers have implanted various techniques to reach RF circuits with higher performance, more functionality such as tunable or reconfigurable, smaller size, lighter weight, lower cost and lowest leakages [3]. However, some techniques, like multilayers [4], Empty Substrate Waveguide (ESIW) [5], Defected Ground Structure (DGS) [6], coplanar waveguide (CPW) [7]..etc, have same disadvantages as big loss of signal, big noise and leakages…etc[3]. Among these techniques, that have been involved to integrate them for RF circuits, it found the Substrate Integrated Waveguide technology (SIW), this component is the base of all modern devices destined to the telecommunication's applications. It is a combination of waveguide and planar transmission lines in planar form, with the some advantages of the two technologies, that have become the first candidate for designing RF circuits [8]. Where, it represents an emerging approach for the implementation and integration of microwave and millimeter components. Thus, it is good means for transmission of information and it can be explained as developed traditional rectangular waveguide but with a dielectric material in the middle (substrate). These devices can be the principal element of RF components as filters.

Filters play important roles in almost electronics circuit and RF/microwave applications. They are used to separate or combine different frequencies. They limit undesirable frequencies and allow the other that are selected for a well-defined application. They have been devised into four types including; high-pass, low-pass, band-pass, and stop-band filters, according to its uses [1]. The SIW technology can play a crucial role in designing a high-pass filter. However, to get a band-pass filter, it should added resonators (via, iris, micro strip line slot,…) in the middle [9]. Otherwise, this component can be miniaturized by using the technique of Half Mode Substrate Integrated Waveguide (HMSIW) [7, 11, 12]. From this, it can be concluded that one of the important priorities in circuit design, is to obtain very suitable, small size, low-loss and noiseless components, that operate at high frequencies and ideal efficiency; which also is the preoccupation of all researchers in the field of communications. In this context, a filter device has been proposed in this research that may meet some of the necessary requirements for optimal performances.

II. THEORETICAL CONSIDERATIONS

The proposed filter is based on Substrate Integrated Waveguide technology known SIW. It is designed with Polyflon Cuflon (tm) substrate that has taken advantage of the qualities of PTFE (Poly Tetra Fluoro Ethylene) and coupled them with the proprietary plating process to produce a microwave substrate. It has unique electrical and physical properties as low loss tangent and dissipation factor, very low dielectric constant, high volume and surface invertness resistivity, high chemical, and almost zero water absorbtion. The substrate thickness used is 0.38 mm with $\varepsilon_r = 2.1$ and tang δ=0.00045 at more than 18 GHz.

Filters based on SIW with inductive shunt coupling may be easily designed with good choice of some parameters like; dimensions of filter as well as width and length, thickness, dielectric constant ε_r, and dissipation factor *tang* δ. Thus, the filter design procedure is similar to this of an air-fielld waveguide filter based on the coupling-matrix technique like represented in [2],[3].

A. Single SIW Cavity Design

Fig.1 represents a single SIW cavity in its basic form. It is designed on the substrate cited above with thickness h, width w_{sub}, and length l_{sub}. This substrate is covered by a top and bottom metallic plates and two rows of metallic holes or vias at the both lateral sides.

The diameter of the via d and the distance between two centers of adjacent vias p, are chosen by analysis calculation with respect of the following equations [3], [8].

$$\begin{cases} d \leq \frac{\lambda_g}{5} \\ p \cong 1.5d \end{cases} \tag{1}$$

$$\lambda_g = \frac{1}{\sqrt{\varepsilon_r\left(\frac{2f}{c}\right)^2 + \left(\frac{1}{w_{eff}}\right)^2}} \tag{2}$$

Where λ_g is the guide wavelength, c the light velocity, f the center resonant frequency, and w_{eff} is the effective width of the SIW that calculate by:

$$w_{sub} \geq w_{eff}\sqrt{\varepsilon_r} \tag{3}$$

The proposed filter operates in the Ka-band, that is from 26.5 GHz to 40 GHz [2]. So, the low frequency equal almost 26 GHz, which can be calculated from the the first cut-off frequency of the mode TE_{100}:

$$f_{cTE_{100}} = \frac{c}{2\sqrt{\varepsilon_r}.w_{eff}} \tag{4}$$

From (4) and (3), the effective width can be found as;

$$w_{eff} = \frac{c}{2f_{cTE_{100}}\sqrt{\varepsilon_r}} \approx 4 \text{ mm}.$$

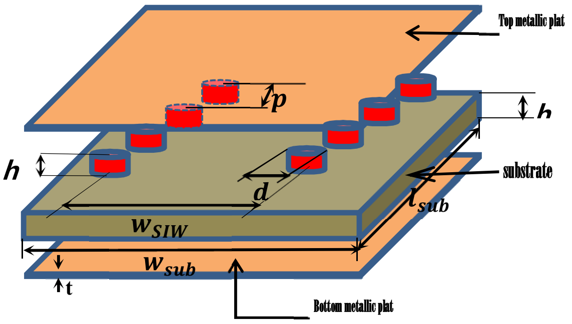

Fig. 1. SIW components.

After defining the parameters p, d, and w_{eff}, the width w_{siw} can be calculated through the following relation [3]:

$$w_{siw} = w_{eff} + \frac{d^2}{(0.95)p} \tag{5}$$

The addition of symmetrical shunt spots with diameters equal to 0.25mm, to the single cavity SIW, can transform it to an narrow band pass filter, thus the return loss is less than -41 dB, as shown in Fig. 2. Where the filter, in this case, has a small size (5.8mm×13.17mm); the results are obtained after simulation with the HFSS software.

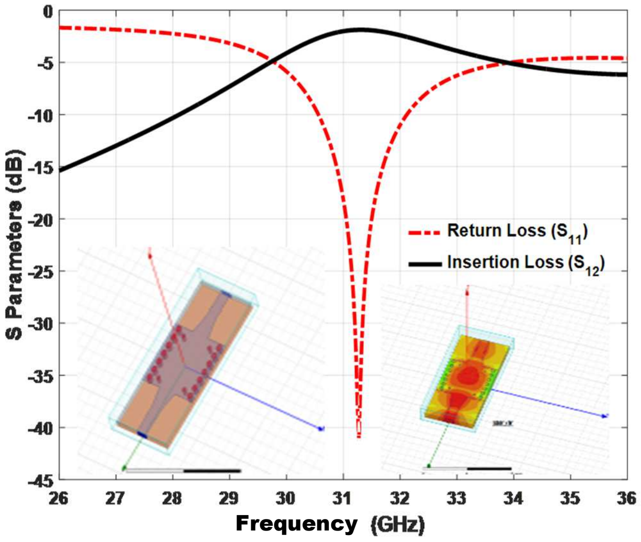

Fig. 2. Simulated S parameters of the first cavity.

B. Filter Design

The SIW cavity can be considered as a traditional rectangular waveguide fulfilled by a dielectric material. Therefore, the modes that can be propagate are TE_{m0n}.

In general, the mode resonant frequency TE_{m0n} for SIW can be calculated as follows:

$$f_{TE_{m0n}} = \frac{c}{2\sqrt{\varepsilon_r \mu_r}} \sqrt{\left(\frac{m}{l_{eff}}\right)^2 + \left(\frac{n}{w_{eff}}\right)^2} \tag{6}$$

Where the mode indices along the *x* and *y*-axis can be represented by *m* and *n*; with l_{eff} and w_{eff} are the effective length and width of the SIW, respectively.

The proposed filter is composed of five cavities, with length *li* that can be calculated as in reference [3]. These cavities are embedded by inductive Iris-coupling post, wherever l_{eff} equal almost to half of the filter's effective length, i.e. the total effective length of the all cavities which constitute this filter. The resonant frequency of the dominant mode is about:

$$f_{TE_{101}} \approx 31.21\ GHz.$$

Therefore:

$$\lambda_c = \frac{c}{f_{TE_{101}}\sqrt{\varepsilon_r}} \approx 6.63\text{mm} \tag{7}$$

It is clearly remarked that the number of cavities which composed the filter, is directly depended to the width of bandwidth of this filter, as shown in Fig. 3, Fig. 4, and Fig. 5, which represent the responses and the E- field distributions of the filter for two, three, and four cavities; and has been summerized in TABLE II.

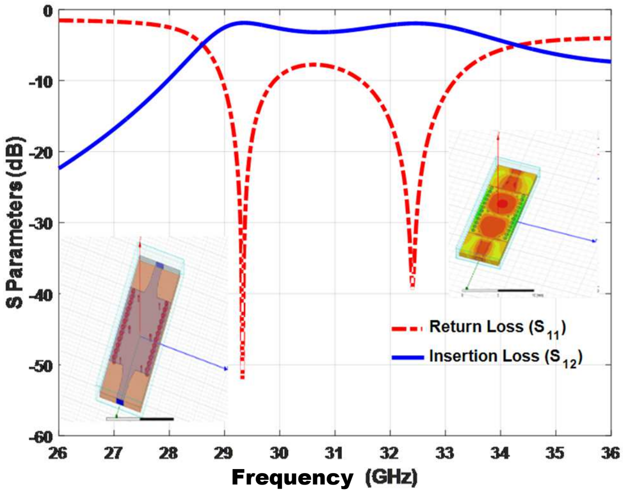

Fig. 3. Simulated S parameters of a second-order filter.

The filter shown in Fig. 3, is designing through two cavities, embedded by inductive posts, with diameters d_1= 0.25mm, and d_2=0.5mm, respectively, where the total length is equal to 17.07mm; and the bandwidth BW≈5.68 GHz. Knowing that the return loss reach -38.54 dB for f=32.41 GHz and -51dB for f=29.3 GHz.

The following device shown in Fig. 4, is designing for three cavities, with symetrical post's diameters d_1=0.25mm and d_2=0.5mm respectively, so the total length of the filter is equal to 20.97 mm; and BW≈ 6.24GHz, with RL less than -45dB for *f* =28.71 GHz and -33dB for 33.45 GHz.

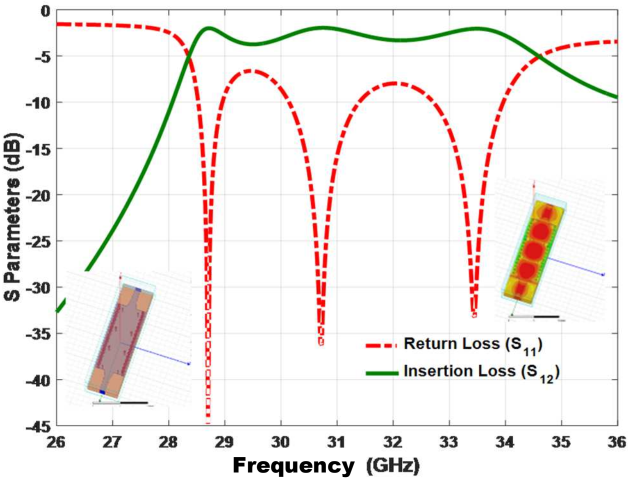

Fig. 4. Simulated S parameters of a third-order filter.

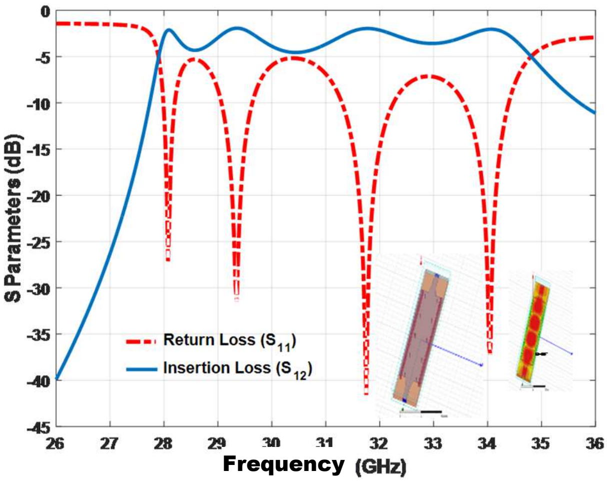

Fig. 5. Simulated S parameters of a fourth-order filter.

The filter shown in Fig. 5, is designing through three inductive posts, with diameters d_1=0.25mm, and d_2=d_3=0.5mm, symmetrically, whose form four cavities, where the total length is equal to 24.87 mm, and the bandwidth BW≈6.9 GHz. Knowing that the return loss reach -42 dB for *f* =31.76 GHz.

The filter proposed in this paper shown in fig. 6, is composed of five cavities that it makes a fifth order filter. These cavities are separated by a pair of inductive post from and distanced two by two at equal horizontal length *li*. These posts play the role of resonators and separators in the same time. Therefore each cavity supports one mode which can be propagate instantly. In order to simplifier the calculations, the vertical distances k_i, between two pair of post, can be equal. All dimensions of the proposed fifth order filter whose are represented in Fig. 1 and Fig. 6; have been analytically demonstrated. They are optimized also by using the EM software (HFSS). Otherwise, all dimension's values are listed in the TABLE I.

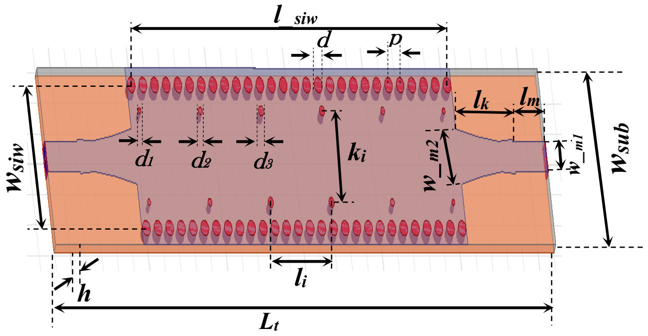

Fig. 6. Proposed filter's dimensions.

TABLE I. THE GEOMETRICAL PARAMETERS OF THE PROPOSED FILTER.

Parameters	Values (mm)	Parameters	Values (mm)
λ_g	3.32	l_i	3.9
d	0.5	$l_{\_siw}$	19.5
p	1.5	d_1	0.2
w_{eff}	4	d_2	0.25
w_{siw}	4.7	d_3	0.33
w_{sub}	5.8	k_i	3
h	0.38	$w_{\_m1}$	1
k_i	3	$w_{\_m2}$	2
l_m ($\approx 2\lambda_g/5$)	1.33	L_t	28.77
l_k ($\approx 4\lambda_g/5$)	2.66	t	0.017

This device is excited through a microstrip line with length l_m , additionally to a tapered one with length l_k, that can be an integer number n from the guide wavelength λ_g. Therefore; $l_m \cong n.\lambda_g$ and $l_k \cong 2.l_m$. In our case $n=2$.

The tapered microstrip line is used for guaranty the transition from quasi-TEM mode of microstrip line to TE_{101} mode of waveguide [13].

For high performance, these microstrip lines that are coupled to excite the SIW BPF, must be adapted in impedance. The impedance of the SIW can be calculated using the following formula (7) [8].

$$Z_{pi} = Z_{TE}\frac{\pi^2 h}{8w_{siw}} \quad or \quad Z_{TE} = \eta\sqrt{\frac{\mu_r}{\varepsilon_r}\frac{\lambda_g}{\lambda}} \tag{8}$$

Where $\eta \cong 377\Omega$; the free space impedance.

The adaptation is achieved through the good choice of microstrip line excitation that has a suitable width for the formula (8) according to Fig. 7.

$$w = \frac{7{,}48.h}{e^{Z_0\frac{\sqrt{\varepsilon_r+1{,}41}}{87}}} - \frac{t}{0.8} \tag{9}$$

Where Z_0 is the characteristic impedance of the microstrip line, which must be adapted to the impedance of the SIW Z_{pi}, and t is the thickness of metallization that is of the order of a few micrometers (≈ 17µm), so it can be neglected to simplify the calculations.

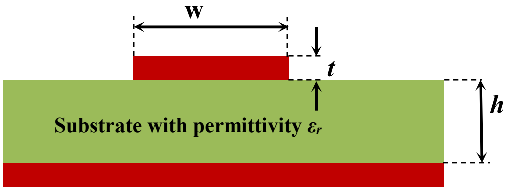

Fig. 7. Vertical section of microstrip line.

TABLE II. FILTER'S CARACTERISTICS FOR DIFFERENT CAVITIES.

Nbre. of cavities / Parameters	1	2	3	4	5
Total width (mm)	5.8				
Total length (mm)	13.17	17.07	20.97	24.86	28.77
f_1 (GHz)	29.77	28.60	28.38	27.89	27.9
f_2 (GHz)	33.74	34.29	34.62	34.7	34.9
BW (GHz)	3.97	5.69	6.24	6.81	7
f_0 (GHz)	31.75	34.29	34.62	31.29	31.9
IL_{max} (dB)	-1.59	-1.49	-1.51	-1.44	-1.47
RL_{low} (dB)	Less than -41	Less than -52	Less than -45	-42	Less than -40

III. SIMULATION AND RESULTS

The above cited conception shown in Fig. 6 is simulated using electromagnetic simulator software HFSS, where the parameters of the design have a total length equal to 28.77 mm and a total width of 5.8 mm, determined analytically based on well-known formulas in the microwave systems. The numerical results in terms of S parameters of the studied filter are plotted in Fig. 8. From this figure, this filter is composed of five cavities each one have one dominant propagation mode. Accordingly, it can be observed five poles with an Return Loss, RL less than -26.5 dB, which can reach less than -40dB dB at the frequency of 32.54 GHz. This frequency is almost equal to the center frequency, referring to the parameter graphs S_{11} sketched in red in the Fig. 8 . In addition, it can be seen that the filter has a wide band, according to the response of this filter at -3dB represented by scattering parameter S_{21} represented in the same graph on green. The operated frequency is from 27.9 GHz to 34.9 GHz, i.e. a frequency range up to 7 GHz. The distribution of the electric field along the surface of the filter is calculated and depicted in Fig. 9 with different angles or shift phases theta (θ). From these distributions, it can be observed that the maximum of this field is concentrated in the middle of the cavities for different values of θ, where it can reach more that $6{,}9 \times 10^4\, {}^{V}\!/_{m}$. As shown in Fig. 9 (a), the E-field is almost symmetrical for phase shift of 80°.

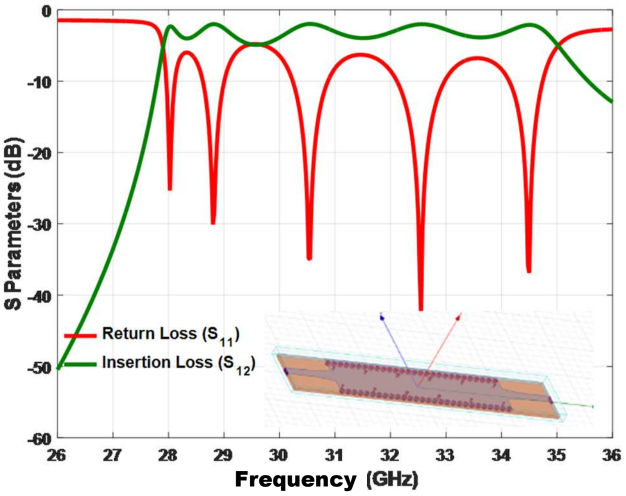

Fig. 8. Simulated S parameters of a fifth-order filter.

According to the E- Field distribution, it can be concluded that the band pass filter proposed in this paper has been good performance; especially, the power received in the excitation port, has been transmitted to the charge, with lower losses and without leakages.

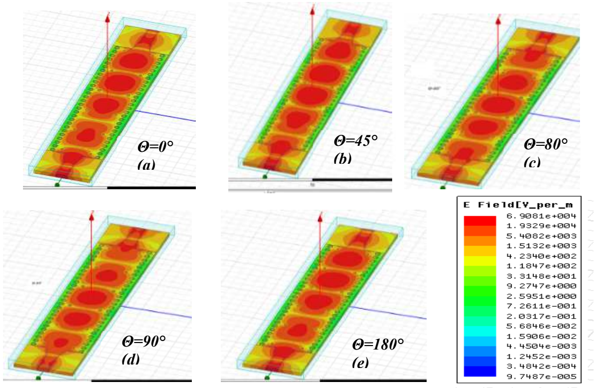

Fig. 9. E-field distribution.

IV. CONCLUSION

A fifth order wide band pass filter is proposed in this paper. It has been designed using the Substrate Integrated Waveguide “SIW” technology, based on iris shunt inductive with height performances; a very low reflection coefficient expressed by S_{11} where it varied from -26.5 dB to less than -40dB. This device has a suitable physical geometry represented as well as small size with total length of 28.77 mm and width of 5.8 mm. It has planar scheme with thickness of 0.38 mm and also characterized by wide band with FBW -3dB equal almost 22%. Therefore, it can work in range from ~ 28 GHz to ~35 GHz, or bandwidth BW= 7GHz. So, this device can be suitable candidate to operate in the *Ka* band, which is reserved for developed communication systems, like the fifth generation of mobile (5G).

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