A Novel Integrated Corrugated Waveguide Bandpass Filter

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***Abstract* —** This paper presents the approach for the design of a X-band bandpass filter using substrate integrated corrugated waveguide (SICW). The SICW filter which is proposed in this paper, is totally realized in a single-layer dielectric substrate with two sequences of metallic vias with the different diameters, and fabricated using a standard PCB process. This proposed filter has the same dispersion characteristics as a waveguide filter, while its dimensions are very shorter than it. A transition circuit between the SICW and 50 Ω microstrip lines was designed for excitation of the filter.

***Index Terms* —** Microstrip bandpass filter, substrate integrated corrugated waveguide (SICW).

I. INTRODUCTION

The waveguide filter is one of the key sections of communication systems with noticeable features such as low insertion loss, high quality factor, and more power transition capability. However, the waveguide equipment has few disadvantages such as expensive fabricating process, difficulty to be integrated in planar circuits because of their large size and non-planar structure. The corrugated H-Plane waveguide filter [1] is the conventional type of these filters which are fabricated using with corrugated sections as direct coupled half wave resonators.

Recently, a novel planar structure technique, called substrate integrate waveguide (SIW) is introduced. This technique has many advantages of printed circuits such as small size, low cost, and easily integration with the microwave and millimeter wave integrated circuits. Many passive and active components based on SIW technique such as mixer [2], coupler [3], phase shifter [4], six ports [5], a circulator [6], diplexer [7], and antennas [8, 9] have been reported recently.

In this paper, a novel design based on the substrate integrated corrugated waveguide (SICW) is represented for realization of waveguide bandpass filter in substrate. SICW consist of two rows of metallic vias, each one operate as one of side walls of waveguide. The other strings of metallic vias with different diameters which are perpendicular to previous ones, act as resonators of waveguide. All results in this paper are obtained using a Ansoft HFSS simulator. A simulated result for the frequency response of conventional corrugated H-Plane waveguide filter and proposed SICW H-Plane filter are in a good agreement as show in this paper.

II. CORRUGATED H-PLANE WAVEGUIDE FILTER

The corrugated H-Plane waveguide filter [1] is one type of these filters which are fabricated using corrugated sections in its H-Plane as direct coupled half wave resonators. This method is based on distributed step impedance bandpass filters that are formulated in [10]. Chebyshev response is considered in this method. Lumped element prototype of bandpass filter and its

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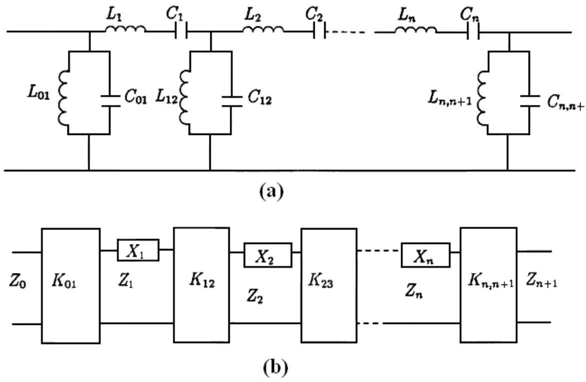
equivalent distributed prototype is shown in Fig. 1. (a), (b).

This approach consists of a cascading of impedance inverters connected by transmission lines. Fig. 1(b) shows the impedance inverters K_{ij} and parallel-resonant circuits of bandpass filter are demonstrated in Fig. 1(a), which are made of the above mentioned inverters.



(a)

(b)

Fig. 1. Equivalent models of the corrugated waveguide filter, (a) parallel-resonant circuits, (b) impedance inverters [1].

The six steps of the procedure of designing corrugated H-plane waveguide bandpass filters are as follows [10]:

1. The guide wavelength of midband λ_{g0} is calculated from this equation:

$$\lambda_{gL}\sin\left(\frac{\pi\lambda_{g_0}}{\lambda_{gL}}\right)+\lambda_{gH}\sin\left(\frac{\pi\lambda_{g_0}}{\lambda_{gH}}\right)=0\,, \tag{1}$$

where λ_{gL} and λ_{gH} are the guide wavelengths for cut off frequencies of the lower f_L and upper f_H, respectively. In case of a narrow-band, we have:

$$\lambda_{g_0}=\frac{\lambda_{gL}+\lambda_{gH}}{2}\,. \tag{2}$$

2. Scaling parameter α is determined from:

$$\alpha=\frac{\lambda_{g_0}}{\lambda_{gL}\sin\left(\dfrac{\pi\lambda_{g_0}}{\lambda_{gL}}\right)}\,. \tag{3}$$

3. The impedance inverter values K_{ij} and the impedance of the distributed element Z are obtained from:

$$Z_n=\frac{2\alpha\sin\left[\dfrac{(2n-1)\pi}{2N}\right]}{y}-\frac{1}{4y\alpha}\left\{\frac{y^2+\sin^2\left(\dfrac{n\pi}{N}\right)}{\sin\dfrac{(2n+1)\pi}{2N}}\right\}-$$

$$\frac{1}{4\alpha}\left\{\frac{y^2+\sin^2\left[\dfrac{(n-1)\pi}{N}\right]}{\sin\dfrac{(2n-3)\pi}{2N}}\right\}\ ,\ n=1,2,\ldots,N\ , \tag{4}$$

and

$$K_{n,n+1}=\frac{\sqrt{y^2+\sin^2\left(\dfrac{n\pi}{N}\right)}}{y}\quad,\ n=0,\ldots,N\,, \tag{5}$$

where

$$y=\sinh\left[\frac{1}{N}\sinh^{-1}\frac{1}{\varepsilon}\right], \tag{6}$$

and N is the number of resonators.

4. The characteristic impedances of the resonators are the same and by scaling the impedance Z_n to oneness, the K-inverters are normalized by:

$$K_{n,n+1}=\frac{k_{n,n+1}}{\sqrt{Z_nZ_{n+1}}}\quad,\ n=0,\ldots,N\,, \tag{7}$$

and

$$Z_0=Z_{n+1}=1\ . \tag{8}$$

5. The asymmetrical impedance inverter is used for presentation of filter structure. The values of the impedance inverters shown in Fig. 2 are realized from following [10]:

$$\begin{gathered}\mathrm{K}=\sqrt{\mathrm{Z_1Z_2}\left(\sqrt{\mathrm{L}}-\sqrt{\mathrm{L}-1}\right)}\\ \mathrm{L}=1+\frac{1}{4}\left\{(\mathrm{a}-\mathrm{d})^2+(\mathrm{b}-\mathrm{c})^2\right\}\\ \mathrm{a}=\mathrm{A}\sqrt{\frac{\mathrm{Z_2}}{\mathrm{Z_1}}}\ ,\ \mathrm{b}=\frac{\mathrm{B}}{\sqrt{\mathrm{Z_1Z_2}}}\\ \mathrm{c}=\mathrm{C}\sqrt{\mathrm{Z_1Z_2}}\ ,\ \mathrm{d}=\mathrm{D}\sqrt{\frac{\mathrm{Z_1}}{\mathrm{Z_2}}}.\end{gathered} \tag{9}$$

In this equation, a, b, c, and d are normalized elements of the ABCD matrix, and Z_1 and Z_2 are normalized guide impedances of the tapered waveguide resonator sections.

The electrical length is calculated by:

$$\begin{cases}\tan 2\phi_1=\dfrac{2(bd-ac)}{\left(a^2-d^2\right)+\left(b^2-c^2\right)}\\ \tan 2\phi_2=\dfrac{2(ab-cd)}{\left(d^2-a^2\right)+\left(b^2-c^2\right)}\end{cases}, \tag{10}$$

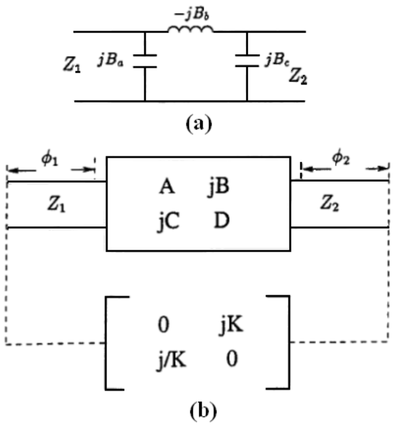


Fig. 2. (a) Equivalent circuit of an asymmetrical iris, (b) equivalent impedance inverter [1].

where the angles φ_1 and φ_2 are expressed in radians.

6. Finally, the physical length of the resonator is obtained from following:

$$l_i = \frac{\lambda_{g_0}}{2\pi}\left[\pi + \frac{(\phi_1 + \phi_{i+1})}{2}\right] . \qquad (11)$$

The mentioned method is used to design a corrugated H-plane waveguide filter with the bandpass extending from 10.31 to 10.33 GHz and a 12.4 dB return loss. The width and height of the standard X-band waveguide are 22.86 mm and 10.16 mm, respectively. The thickness of the waveguide is considered as 2 mm. Its side and top view are shown in Fig. 3.

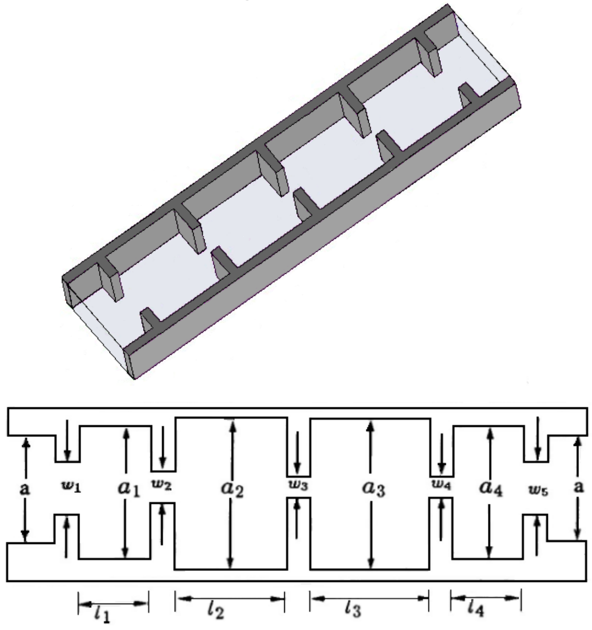


Fig. 3. Side and top view of corrugated standard waveguide filter.

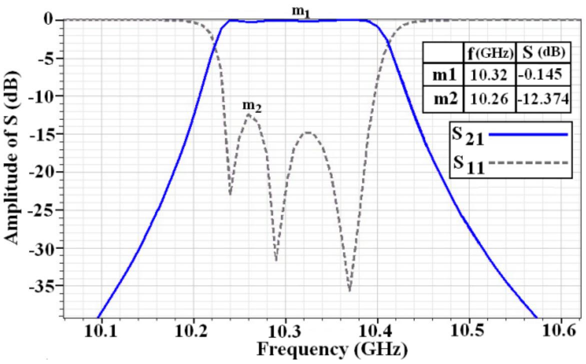


Fig. 4. Simulation result of corrugated standard waveguide filter.

Demonstrated dimension in Fig. 3 are shown in Table 1 where all dimensions shown in millimeters.

Table 1: The parameters of Fig. 3

Parameter	Value	Parameter	Value
$l_1=l_4$	16.283	$w_2=w_4$	6.206
$l_2=l_3$	17.715	w_3	5.79
$w_1=w_5$	10.055	$a_1=a_2=a_3=a_4$	22.86

Simulation results of the designed filter are shown in Fig. 4 which is obtained by Ansoft HFSS.

III. SUBSTRATE INTEGRATED WAVEGUIDE

Substrate integrated waveguide is a new type of planar structure which is based on a low-cost printed circuit board (PCB) process similar to microstrip, stripline, or coplanar waveguides. The SIW is implemented on a substrate using arrays of metallic vias which take the roll of the side walls of waveguide. The transmission to planar structures such as microstrip, stripline, or coplanar waveguide is designed and integrated on the same substrate. SIW components can be integrated together without any transmission circuit. The performance of the SIW component, such as insertion loss, quality factor, and power transmission, is better than the performance of microstrip, stripline, or coplanar waveguide.

However, the analysis of via structure of the SIW component is much more complicated than the conventional waveguide devices. Characteristics of the SIW component can be achieved using a generalized BI-RME method [12].

It was assumed that a TE_{10}-like mode in the SIW has similar dispersion characteristics to TE_{10} mode of a dielectric filled rectangular waveguide with an equivalent width. This equivalent width is known as effective width of the SIW (see Fig. 5). Other the important parameters of SIW are the diameter of vias (D) and the distance between them (b).

The SIW parameters of Fig. 5 can be approximated as follows [13, 14]:

$$\left[W = a_{rwg} + \frac{D^2}{0.95b}\right] . \qquad (12)$$

The practical conditions which shall be considered are as follow:

$$(b-D) \le 0.2\lambda \text{ and } (b-D)/D \le 0.5 .$$

If (b-D) is greater than 0.2λ, the power leakage between adjacent vias will increase. If the diameter of via holes (D) is over the range, the reflection loss of the SIW filter will be great.

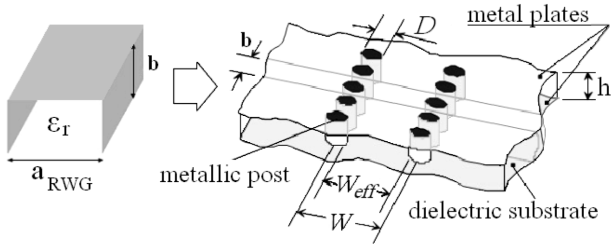


Fig. 5. Filled waveguide to substrate mapping and SIW parameters [8].

Since the field distribution in SIW component is similar to the conventional rectangular waveguide, it is possible to use the same equation to calculate the cut-off frequency of the SIW:

$$f_c^{mn} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \cdot \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} . \qquad (13)$$

Equation (5) can be writing as follows:

$$f_c^{10} = \frac{1}{2\pi a} \cdot \frac{1}{\sqrt{\mu_0\varepsilon_0}} \cdot \frac{1}{\sqrt{\varepsilon_r}} . \qquad (14)$$

IV. SUBSTRATE INTEGRATED CORRUGATED WAVEGUIDE FILTER

Figure 6 shows the arrangement of a substrate integrated corrugated waveguide (SICW). The SICW filter is designed based on the "Taconin TLY(tm)" subtracted with following characteristics:

$$h = 0.81mm,\ \varepsilon_r = 2.2,\ \tan\delta = 0.0009$$

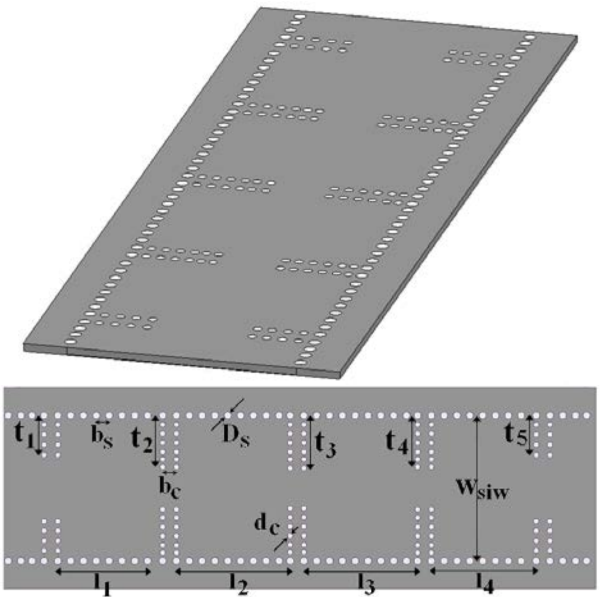


Fig. 6. Side and top view of substrate integrated corrugated waveguide filter.

Table 2: The parameters of the SICW filter

Parameter	Value	Parameter	Value
t_1	4.33	l_1	12.94
t_2	5.63	l_2	13.91
t_3	5.77	l_3	13.91
t_4	5.63	l_4	12.94
t_5	4.33	Wsiw	15.93
D_s	0.8	bs	1.5
d_c	0.6	bc	1.5

The diameter of the side vias (D_S) and the corrugated section vias (d_S) is chosen 0.8 mm and 0.6 mm, respectively. Other parameters of Fig. 6 are shown in Table 2 where all dimensions shown in millimeters. According to the Table 1, it is recognized that width, height, and length of the filter are reduced noticeably.

V. EXCITATION MECHANISM OF SICW

Different structure maybe proposed for the excitation of the SIW structures. A conventional type is made of a tapered microstrip line between the SIW section and 50 Ω microstrip lines. This plane is shown in Fig. 7.

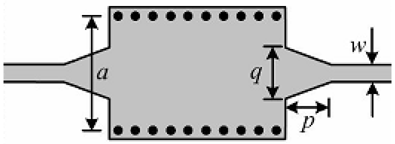


Fig. 7. Transmission SIW to microstrip lines.

The width of SICW (q) is achieved from input impedance, and the width of excitation port (w) is calculated based on the 50 Ω microstrip lines [15]. The length of transmission line (p) is optimized by the Ansoft HFSS. The above mentioned parameters are as follows:

$$q = 13.6\,mm,\, w = 2.25\,mm,\; p = 13.5\,mm$$

Top views of the proposed SICW filter are illustrated in Fig. 8.

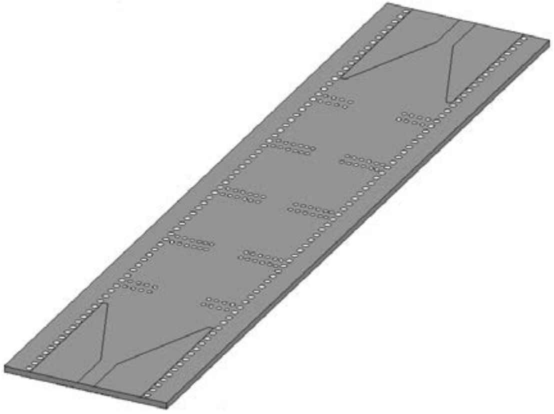


Fig. 8. Top view of SICW filter with transmission to microstrip line.

The designed SICW filter is simulated by Ansoft HFSS in bandwidth of 10.15-10.45 GHz and the results are shown in Fig. 9.

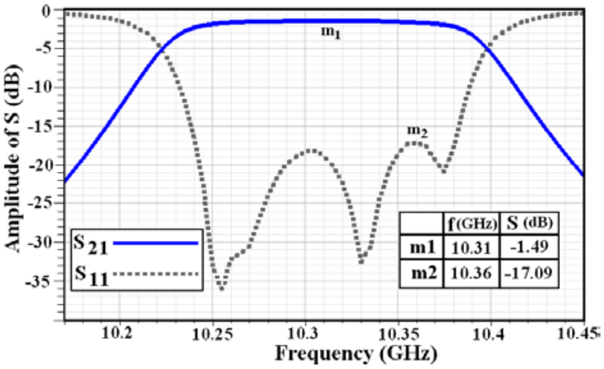


Fig. 9. Simulation result of designed SICW filter.

According to Fig. 9, return and insertion loss are better than 17.1dB and 1.49 dB, respectively.

VI. EXPRIMENTAL RESULT

The proposed filter is fabricated and the Fig. 10 shows this prototype.

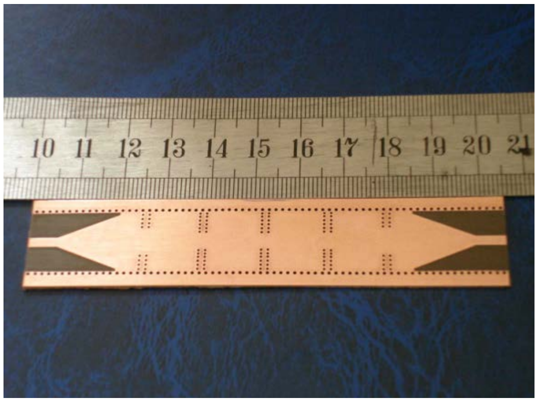
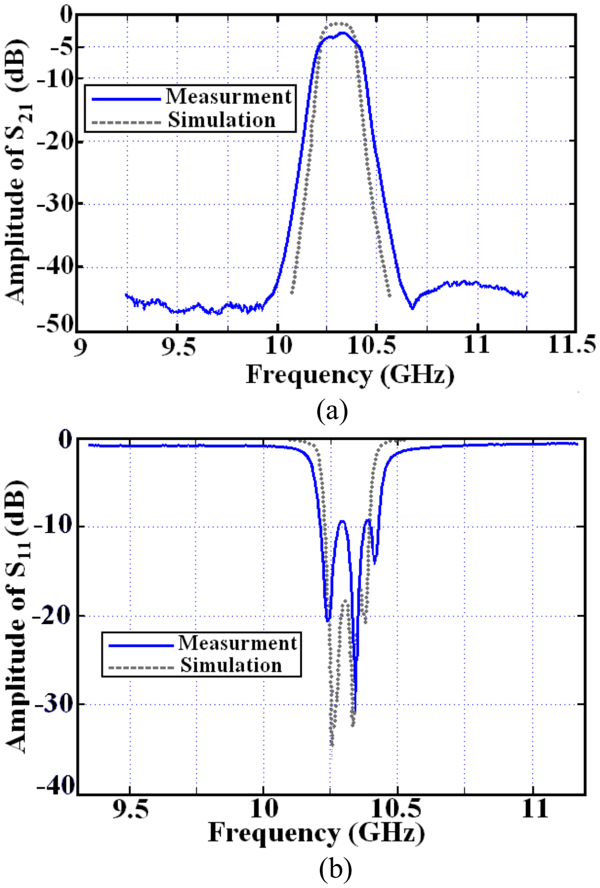


Fig. 10. Fabricated SICW filter.

The scattering parameters of the fabricated filter are measured by Agilent 8720-B Vector Network Analyzer (VNA) and the results are shown in Fig. 11.



(a)

(b)

Fig. 11. Measurement and simulation result of SICW filter, (a) insertion loss, (b) return loss.

As it is observed in Fig. 11(a), insertion loss of the fabricated model is 2.4 dB at the center frequency, which is about 1 dB higher than the simulation results. In addition, return loss of the fabricated model is 17 dB, which is close to simulation results, as seen in Fig. 11(b). By comparing Fig. 11(a) and (b), we observe a good accordance between them.

VII. CONCLUSION

A novel single-layer planar X-band SICW filters is presented in this paper. The prototype of this filter is designed, simulated, and fabricated using a PCB process and measured with a VNA. This proposed SICW filter is totally developed by metallic vias with different diameters on a single-layer substrate, and has the same dispersion characteristics as a waveguide filter, while its dimensions are very smaller than it. The width and height of standard waveguide is 22.86 mm and 10.16 mm while the width and height of SCIW is 22 mm and 0.81 mm, respectively; this shows a reduction ratio of about 12.5 in the height of the filter. This approach has some advantages such as compact size, low weight, and low cost. So, it is a suitable choice for designing microwave and millimeter-wave planar circuits.

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