SIW-DGS Bandpass Filter Design for C Band Satellite Communications

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Abstract. In this paper, a bandpass filter is designed and fabricated for C-band satellite communication applications. The substrate integrated waveguide (SIW) and defected ground structures (DGS) are used in the design process. CST Microwave Studio software is used to analyze and design the proposed filter. It is built over DiClad 880 laminate having a thickness of 0.508 mm, and formed by etching three cascaded DGS cells on the SIW's top plane. There is a good agreement between the simulated and measured results. The filter is centered at 6.175 GHz with 500 MHz bandwidth (8.1% fractional bandwidth) in line with applicable US Federal Communications Committee Rules. The simulated insertion loss at the center frequency is around 0.80 dB and the return loss in the passband is better than 30 dB. The measured minimum insertion loss is 1.4 dB, and the measured return loss in the passband is better than 14.5 dB. The obtained results are presented, discussed, and compared with other studies. It can be said that the features of the proposed filter such as size, order, return loss, insertion loss, upper band rejection, etc. are better than those of many other filters given in the literature.

Keywords. Bandpass filter, substrate integrated waveguide, defected ground structure, satellite communication.

1.Introduction

RF/Microwave Filters operating within C-band are utilized in satellite telecommunication systems. For these systems, the metallic waveguide-based filters are mainly implemented due to their high performance. However, they are heavy, bulky, and hard to manufacture. On the other hand, after the arising of the Substrate Integrated Waveguide (SIW) technology, the ability of the planar technologies has been pushed up to a higher level and the SIW-based filters have been started to offer better performance compared to the metallic waveguides at a low cost and lightweight.

SIW was first presented by Hirokawa J. and M. Ando [1], and it was introduced by Wu et al [2]. The SIW-based structures are manufactured using the printed circuit board realization methods. They are similar to the dielectric-filled rectangular metallic waveguides, where rows of metalized via holes form the sidewalls, and the upper and lower copper layers of the waveguide. They have the properties of both micro-strip lines and traditional cavity waveguides [3].

Defected Ground Structure (DGS) was first proposed by Korean scholars [4]. It can be integrated within transmission lines (TLs) to realize the compact low pass filters using the bandgap effect [5]. DGS concept is realized by etching the simple or more complicated structures to the ground plane. They cause a defect in the flat ground plane of the TLs and hence the name DGS. Although this term is related to the ground, it can be etched to both the upper and bottom planes of the SIW. It has a more dominant effect when it is etched to the top plane. DGS cells can be used in the cascaded form for better performance. The characteristics of the DGS cells are controlled by the shape and dimensions of the cell [6].

One of the main motivations of this study is to emulate the non-planar 5th-order filter performed using single-mode TM resonators in [7], and get better results than that study with less order. For this purpose, a 3rd-order SIW-DGS bandpass filter (BPF) has been preferred to offer good performance compared to the performance of expensive bulky metallic waveguides.

Another aim is for the design to operate only between 5.925 and 6.425 GHz, with a center frequency of 6.175 GHz and bandwidth (BW) limited to 500 MHz in accordance with applicable US Federal Communications Committee Rules [8] Because these band range and BW value are currently allocated in the United States exclusively for non-Federal use on a primary basis for FSS (Earth-to-space) and FS. For FSS, the 5.925-6.425 GHz band (Earth-to-space) is associated with the 3.7-4.2 GHz band (space-to-Earth) and referred to collectively as the C-band. There are about 1,535 earth station licenses in the 5.925-6.425 GHz band [8,9]

In light of above information, the band range has been achieved at the desired level, the proposed filter has a 3 dB BW of 500 MHz and offers a flat group delay of around 1.3 ns within the passband. The minimum measured insertion loss (S_{21}) is 1.1 dB, and the return loss (S_{11}) in the passband is better than 15 dB. It is suitable for use in C-band satellite communication applications and has better features than many other filters whose specifications are given in the comparison table in Discussion Section.

In the remainder of this section, some studies using SIW only, DGS only, and SIW and DGS together are mentioned. Then, the design methodologies are given in Section II. The findings are discussed in Section III. Finally, the study is concluded in Section IV.

Different SIW filter designs can be found in the literature. In the study [10], two versions of the SIW filters for use in C-band applications were proposed. The first design was a sixth-order filter and operated at 4 GHz with a relative BW of 6.25%. It was designed to reject 3.37–3.75 GHz and 4.25–5 GHz frequency bands. As the size reduction is so large for the proposed filter, an eighth-order filter was also designed.

The filter proposed in [11] has a fractional BW of 38% and a center frequency of 6.9 GHz with a ripple of 0.1 dB. The ceramic substrate with a relative permittivity of 90 was used. In the study of [12], a wideband SIW BPF with 64.7% fractional BW centered at 4.67 GHz frequency was presented. The total circuit dimension excluding two 3 mm feeding lines was 12.6 x 47.9 mm^2. Besides the papers cited above, many other studies are using SIW technology to design different filters [13-15]. Important data about all these studies are given in Table 2 for comparison purposes.

Several filter designs with DGS structures can be found in the literature. In the study of [16], a novel design of a dual-band BPF with a controllable second passband was proposed. The size of the filter including the input and output ports was 45 x 20.6 mm^2. In the paper [17], three types of band filters were presented. DGS-based modified stepped impedance resonator was used for designing the filters. One of these filters was single band BPF which had the passband from 2.7 to 4.5 GHz with 50% BW.

A compact-sized (26.8 x 16.5 mm^2) wide-band BPF with high performance for WiMAX applications was introduced in [18]. The filter had a center frequency of 5.3 GHz and a 3 dB BW from 4.2 GHz to 6.4 GHz. The DGS was used to enhance the rejection level of the filter. In addition to the papers cited above, many other studies are using the DGS method [19-21]. Important data about all these studies are given in Table 2 for comparison. In the studies shared so far, either only the SIW or only the DGS method had been preferred. However, SIW can work as a high pass filter having a dominant cut-off frequency equal to the dominant TE10 mode cut-off frequency, whereas the DGS provides a band rejection. The BPF response can be yielded more effectively by combining these concepts. Some of the SIW-DGS BPF designs will be given in the following paragraphs.

A compact SIW-DGS-based filter was presented in [22] for use in satellite communications. The size and center frequency were 23.8 x 10 mm^2 and 13.9 GHz, respectively. In another study, a SIW BPF using DGS with complementary split-ring resonators was proposed. Two passbands were obtained between the frequency range of 2 and 14 GHz. The center frequency of the first passband was 5.4 GHz BW of 17.2%. The center frequency of the second passband was 10.1 GHz with a BW of 55.2% [23].

A compact-sized SIW-DGS BPF was proposed in [24]. The center frequency and fractional BW of that filter were 9 GHz and 32%, respectively. The S_{21} at the center frequency was around 0.80 dB and the S_{11} in the passband was better than 20 dB. The upper-band rejection was more than 35 dB between 13 GHz and 18.5 GHz. Besides the papers cited above, many other studies are using SIW-DGS technology [25-27]. The features of them can be seen in Table 2.

2. Filter Design Methodology

2.1. SIW Analysis

SIW is a straightforward integration of a rectangular waveguide into a microstrip substrate. Relatedly, the equations governing the SIW design are revised versions of the rectangular waveguide's analytical equations. The leakages and band gaps may arise within the operating band due to the periodic structure of the vias in SIW designs.The design parameters have an important role in determining the cut-off frequency.

There is an inverse relationship between W_{SIW} and cut-off frequency. According to this; as the SIW width increases, the frequency shifts towards a lower frequency [28-30]. In connection with this, the design rules stated in [31] have been followed during the process. These rules are given in Equations (1) and (2).

$$p \leq 2d \quad (1)$$

$$0.2 \geq p / \lambda_c \geq 0.05 \quad (2)$$

where λ_c is the cut-off wavelength.

Figure 1 shows the SIW structure used in the design. The tapered transition has been preferred to provide better impedance matching and excite the SIW by using a microstrip port.

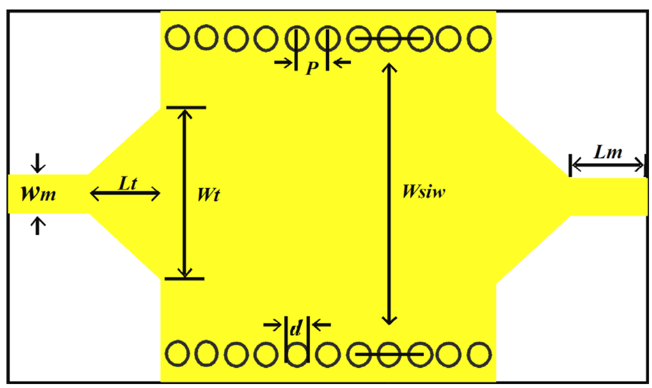


Figure 1. The top plane of the SIW structure

2.2. DGS Cell Analysis

A novel DGS unit cell which was proposed by [32] is given in Figure 2. It offers better performance than some popular simple DGS cells such as square head slots, circular head slots, dumbbell slots, and arrowhead slots, without adding extra complexity to its geometry. It can be more conveniently incorporated in the top plane of the SIW structures rather than etching in the ground plane to provide the stopband response. These advantages set it apart from other traditional cells. It can provide a deep wide-bandgap with the rejection of –30 dB in the 8–16 GHz frequency range. The resonant frequency can be controlled by the geometry and dimensions of the cell as illustrated in [32].

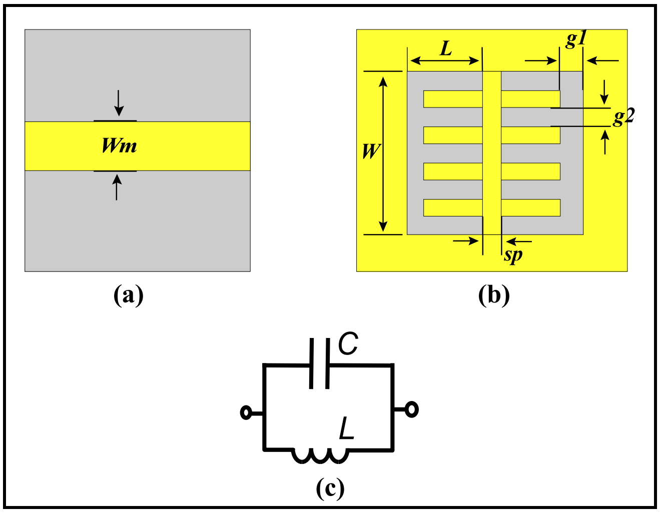


Figure 2. a) Microstrip line, b) DGS structure, c) DGS cell equivalent circuit.

To get the initial dimensions that can provide the desired band rejection, the DGS cell was firstly etched to the ground plane of the microstrip transmission line to perform a fast parameter sweep. The microstrip line has a width of 4 mm. The dimensions of the DGS cell are as follow: W = 8.47 mm, L = 2.5 mm, $g1$ = 0.5 mm, $g2$ = 0.6 mm, and sp = 0.8 mm. All of these parameters can be seen in Figures 2 (a) and (b). The DGS cell can be represented using an equivalent parallel resonance circuit as in Figure 2 (c). Equivalent circuit parameters can be expressed as in Equations 3 and 4 [33].

$$C_p = \frac{5f_c}{\pi\left[{f_p}^2 - {f_c}^2\right]}\ \text{pF}, \qquad (3)$$

$$L_p = \frac{25}{C_p\,(\pi f_p)^2}\ \text{nH}, \qquad (4)$$

2.3. SIW-DGS BPF Design

As mentioned before, SIW works as a high-pass filter. DGS cells can provide a bandgap and act as a low-pass filter if combined with the TL The BPF response can be achieved more effectively by combining these two structures. Accordingly, the filter is created by loading the DGS cells to the upper plane of the SIW. In the design, three cascaded cells which form a '3rd-order SIW-DGS BPF' were preferred for the sake of providing better response, rejection, and sharper transition from passband to stopband.

The configuration of the filter is shown in Figure 3. An initial design was established based on the empirical formulas and design criterias available in the literature for SIW. Then, the dimensions in Table 1 were obtained after fine-tuning using the optimization feature of the 3D simulator (CST). The design is scalable. The lower cut-off frequency is controlled mainly using the width of the SIW. The upper cut-off frequency is controlled by scaling the geometry of the DGS unit cells.

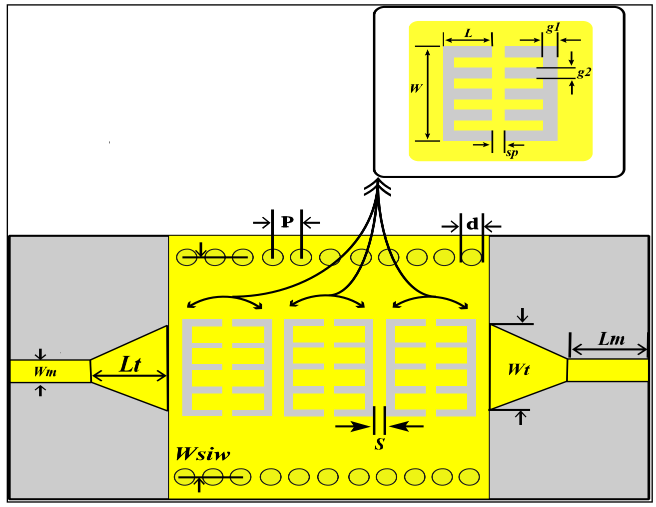


Figure 3. The configuration of the 3rd order SIW-DGS BPF

Table 1. Dimensions of the proposed SIW-DGS BPF

Symbol	Value (mm)	Symbol	Value (mm)
Wm	1.519	*sp*	0.8
Lm	3.8	*s*	0.8
Wt	7.587	*L*	2.5
Lt	4.7	*W*	8.47
Wsiw	16.25	*g1*	0.5
d	1	*g2*	0.6
P	1.9	*SubTh*	0.508

In the design, SIW was adjusted to provide a high pass filter with a cut-off frequency of 5.925 GHz, while DGS cells were tuned to provide a low pass response with a cut-off frequency of 6.425 GHz. Standing on the above analyses of the SIW and DGS, the filter was centered at 6.175 GHz with 500 MHz BW as seen in Figure 4.

The passband S_{11} is better than 30 dB, and the S_{21} at the center frequency is around 0.80 dB. There is a sharp transition from the upper 3-dB edge frequency located at 6.425 GHz to a zero transmission point located at 7.4 GHz. The spurious responses appearing at 10.05 and 10.38 GHz are lower than -12.2 dB.

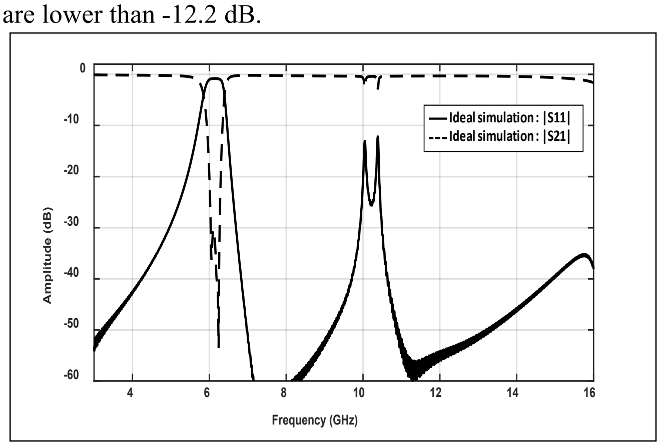


Figure 4. Simulated S-parameters of the proposed filter

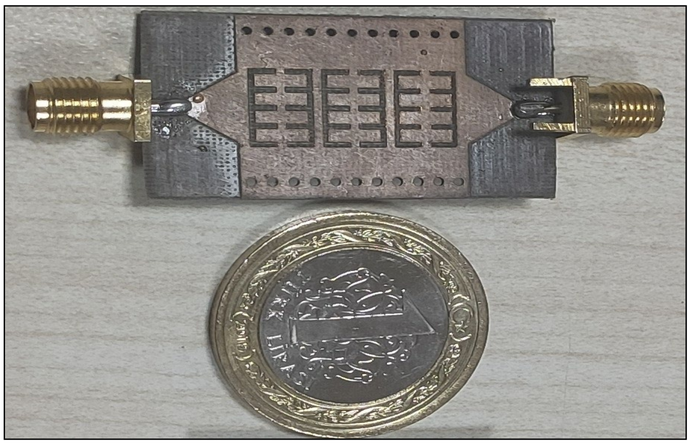
3. Validation Results and Discussion

3.1. Results

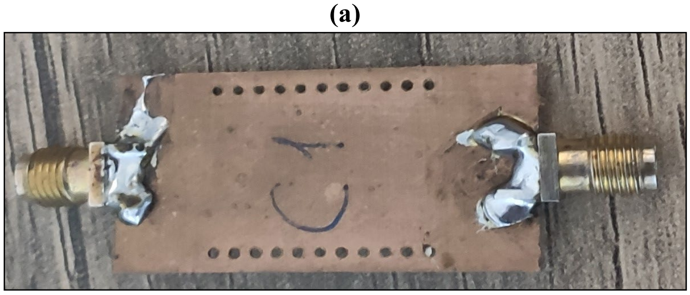
For the sake of validating the concept, a prototype of the engineered filter was manufactured and measured. The manufactured prototype is shown in Figure 5. It was built over DiClad 880 laminate that has a thickness of 0.508 mm.

Figure 6 illustrates the measured S-parameters versus simulation results and simulation results with the inclusion of the SMA connectors into the 3D simulation. There is a good agreement between the simulation results before and after the inclusion of the connectors; However, the inclusion of the SMAs affects the impedance matching of the filter. Figure 6 shows both in-band and out-band responses of the filter by taking into account practical concerns.

As for the measurement, there is a good agreement between the simulated and measured results. With some deviation due to manufacturing quality, there is a relaxation in the lower cut-off edge due to the metallization coating quality of the via-holes which is directly related to the lower cut-off edge. According to the measurements, the spurious response due to the iris resonances (located outside the frequency band with rejection specifications) appearing at the 10.4 GHz is still less than 18 dB. Meanwhile, there is a very wide isolation of better than 18 dB in the upper cutoff region 6.7 up to 16 GHz. Figure 7 represents group delay for both the measurement and simulation. The filter provides a considerably flat measured group delay of around 1.2 ns within the passband, and it is 0.4 ns less than the group delay extracted by simulation.



(a)



(b)

Figure 5. Manufactured prototype, a) Top view b) Bottom view

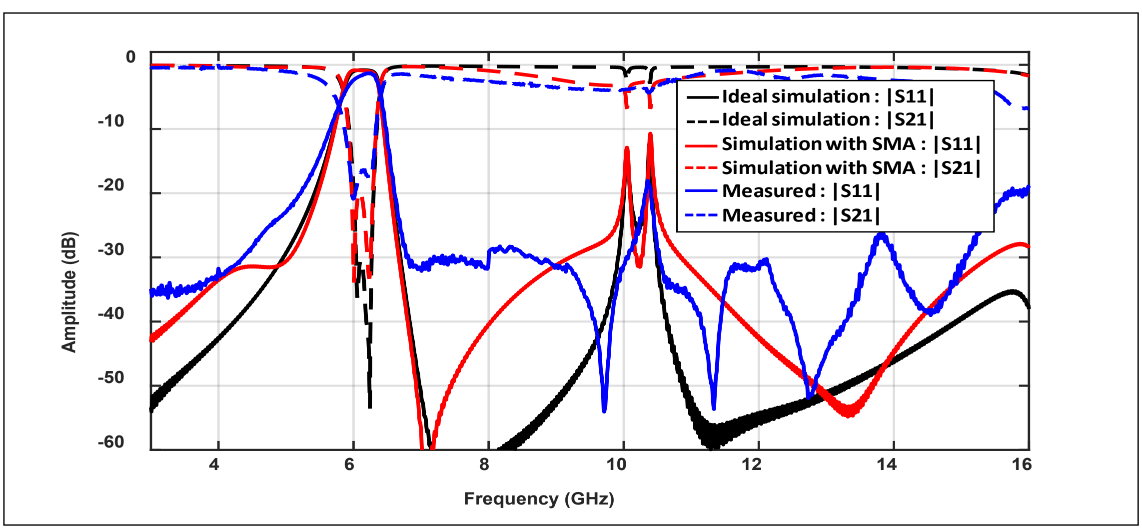


Figure 6. Measured and simulated scattering parameters of the proposed filter

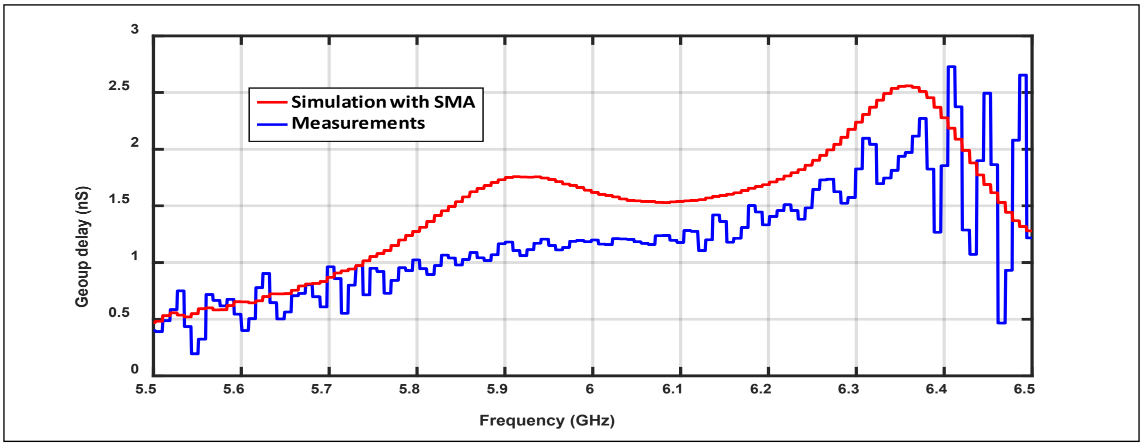


Figure 7. The simulated and measured group delay of the proposed filter

3.2. Discussion

The proposed 3rd order SIW-DGS C-Band filter preserves the compactness property with a total size of 20 x 37.9 mm^2. It offers good performance when compared with filters that were proposed in some other studies. For example, one of these filters is the non-planar 5th order C-band filter realized by using single-mode TM resonators introduced by Tomassoni C., et al. [7]. The full-wave simulated response of that study is given in Figure 8. If a comparison is made between the high-performance non-planar filter of [7] and our planar filter, it can be said that the latter has good performance as the SIW performance is better against spurious response.

There is a sharp transition to the zero transmission of -68 dB which is lower than the results obtained in that study. As noted in [7], even if the TM filter was carefully designed to locate outside the frequency band with iris resonance rejection capabilities, the filter response is not fully compatible with out-of-band characteristics at 10-11 GHz. The detailed comparison results are given in Table II. Important data about the filters designed in our work and proposed in [7] can be seen there. Furthermore, the features of many SIW filters, DGS filters, and SIW-DGS filters are given in the same table.

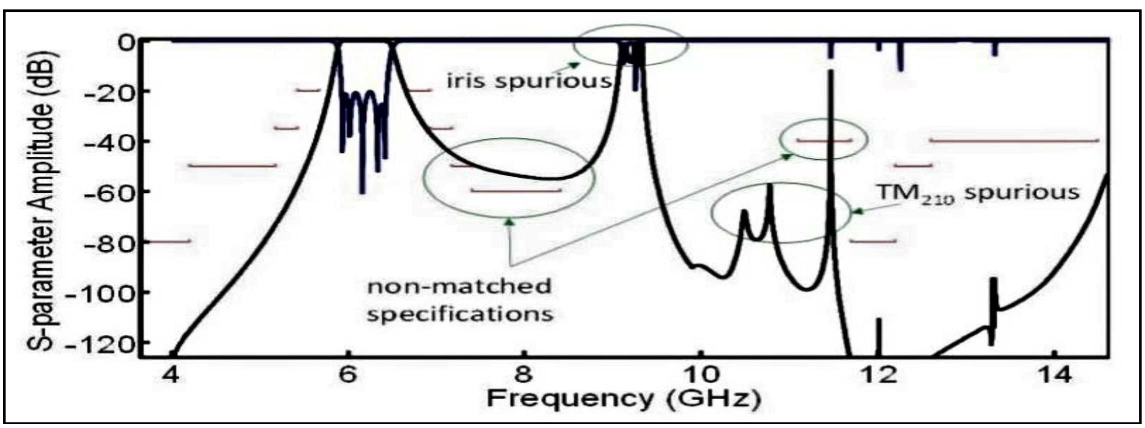


Figure 8. Measured and simulated S-parameters of the filter proposed in [7]

Table 2. Comparison of some filters presented in references

References	Size (mm²)	Technology	Order	Center Frequency (GHz)	FBW (%)	RL (dB)	IL (dB)	Upper Band Rejection
[8]	26.3 x 14.2	SIW	*6*	4	7.2	> 30	2.6	35 dB, 4.25 – 5 GHz
[9]	13.6 x 4.4	SIW	*3*	6.9	38	> 16	1.26	30 dB, 5.6 – 6.6 GHz
[10]	12.6 x 47.9	SIW	---	4.67	64.7	> 12,1	1	20 dB, 6.7 -12.8 GHz
[11]	8 x 12.4	SIW	---	2.58	10	23	1.68	0.141 dB/MHz
[12]	12 x 21	SIW	---	3.5	---	> 10	< 3	15 dB, 3.75 – 5 GHz
[13]	40 x 47	SIW	---	5.25	7.6	> 16	1.5	30 dB, 5.48 – 7.8 GHz
[14]	30 x 15	SIW	*5*	8.5	42	> 11	< 1.1	20 dB, 10.35 – 15 GHz
[15]	45 x 20.6	DGS	---	1.57	16.8	18.9	0.59	---
[16]	0.4 x 0.37 $(\lambda g)^2$	DGS	---	3.1	50	16	3	17 dB, 4.6 – 4.8 GHz
[17]	26.8 x 16.5	DGS	---	5.3	41.5	> 12	< 0.5	12 dB, 7.0 – 10.0 GHz
[18]	18 x 7.8	DGS	---	4.8	83.3	40	0.8	15 dB, 8.0–11.0 GHz
[19]	11 x 21	DGS	*2*	5.7	60	25	0.2	14 dB, > 8 GHz
[20]	$\pi\,(0.11\lambda g)^2$	DGS	---	2.6	36.2 – 46.5	> 15	0.8	15 dB, > 3.5 GHz
[21]	30 x 16	DGS	---	7	118	> 20	< 2	20 dB, > 12 GHz
[22]	23.8 x 10	SIW & DGS	---	13.9	3.5	35	< 2	> 28 dB, > 16 GHz
[23]	0.59 x 0.51 $(\lambda g)^2$	SIW & DGS		5.4 & 10.1	17.2 & 55.2	25 & 40	1.1&1.4	> 15 dB, > 8 GHz
[24]	0.36 $(\lambda g)^2$	SIW & DGS	*3*	9	32	> 20	0.8	> 35 dB, 13.0–18.5 GHz
[25]	0.39 x 0.39 $(\lambda g)^2$	SIW & DGS	---	4.9	9.2	> 18	1.1	> 30 dB, > 6 GHz
[26]	0.42 x 1.27 $(\lambda g)^2$	SIW & DGS	---	5.75	3.66	> 30	2.05	---
[27]	1.71 x 0.68 $(\lambda g)^2$	SIW & DGS	---	8.98	47.4	> 18	1.5	Roll-off Rate = 58 dB/GHz
[7]	**70 x 50**	**TM&CombLine Resanators**	***5***	**6.175**	**8.3**	**> 20**	**0.2**	**---**
This Work	**20 x 37.9**	**SIW & DGS**	***3***	**6.175**	**8.1**	**> 30**	**0.8**	**> 50 dB, 7.0–9.2 GHz**

4. Conclusion

Nearly all C-band communication satellites use the band of frequencies from 3.7 to 4.2 GHz for their downlinks, and the band of frequencies from 5.925 to 6.425 GHz for their uplinks. In this paper, a novel compact-sized BPF operating at 5.925-6.425 GHz was proposed for the C-band satellite communication applications. It was mainly designed to simulate peer filter of the non-planar waveguide technology, and prove the ability of cheap SIW technology to offer good performance comparable to the expensive bulky metallic waveguides' performance. The SIW method provides the characteristics of a high pass filter, and three DGS cells provide a sharp upper-out of band rejection. The simulation result was obtained in the 3D simulator. The fractional BW of the proposed filter is 8.1%. It was observed that the filter offers almost a flat group delay in the passbands. There is a good agreement between the simulated and measured results after taking into consideration the presence of the SMAs.

In comparison with some structures, the proposed filter offers good performance in terms of size, order of the filter, upper band rejection, RL, IL, and BW. The design can easily be used in rocket-like space applications. However, because the fabricated prototype is very thin (approximately 0.5 mm) and there is no laboratory facility, the space test was not carried out and could not be done. Since the filter consists of passive elements, it is predicted to pass the vibration test. But, no comment can be made on the temperature test.

In conclusion, the outcomes of the work spot the light on the validity and ability of SIW-DGS technology in designing high-performance wideband filters. To improve this work, further size reduction can be done using Half Mode SIW. Also, the filter can be supplemented with DGS or spur lines at the input and output ports to produce other transmission zeros and enhance stopband performance.

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