Design and Analysis of a Compact Substrate Integrated Waveguide Bandpass Filter for Ku Band Applications

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***Abstract*–The Substrate Integrated Waveguide (SIW) filter is widely used in various RF communications to receive only the desired frequency with least delay. However, the design of SIW filters having high efficiency, compact size and low cost is still a design challenge. In this research work, a compact SIW bandpass filter with tapered via transition and multiple 'U' shaped slots is proposed for the Ku band applications. The proposed filter uses a tapered via transition to provide a smooth transition from microstrip line (planar structure) to SIW (waveguide structure) with minimal reflection which results in better S_{11} performance and wider bandwidth. The stopband performance of the proposed filter is improved significantly by introducing four numbers of 'U' shaped slots in the SIW structure which introduces transmission zeros in the upper stopband. The simulated results obtained from HFSS v.14 shows that the proposed filter has improved performance parameters such as low reflection, high isolation, minimal group delay, etc which make it suitable for Ku band applications.**

Index Terms— Substrate integrated Waveguide (SIW) filter, tapered via, group delay, isolation, radiation loss.

I. INTRODUCTION

Wireless communications occupy a vital and majority portion of communication throughout the globe. Microwave filters are widely used device to differentiate between wanted signal frequencies and unwanted signal frequency in satellite communications, mobile communications, etc. [1]. Substrate Integrated Waveguide (SIW) filter has been used for design and implementation of RF broadband systems due to its low-cost [2], planar structure [1], compactness, ease of fabrication, relatively low-loss [3], high-Q factor [3], high performance [2], etc. SIW technology is more advantageous for low-cost and mass-production over the classical waveguide technology as it eliminates the tedious and expensive pre and post-fabrication processes [4]. Dielectric waveguide suffers from two fundamental problems such as radiation loss due to discontinuity and difficult modal transition to planar circuits [4]. These are solved by a hybrid design technology [4] consists of the good qualities of waveguide structures (i.e. high power handling capability) and planar structure (i.e. ease of fabrication, low-cost). A good in depth fundamentals of SIW filters are presented in [4], [5]. A novel wideband feedline, i.e. transition from microstrip line to SIW is proposed using two extra vias across the tapper structure [6]. Symmetric inductive vias are used to improve the stop band rejection capability of SIW filters [2]. An efficient design formula for the width calculation of SIW structure is derived from a mode-matching approach which minimizes the reflections from the junction between the SIW and an all-dielectric waveguide of equal width [3]. Various methods to design a bandpass SIW filter with the introduction of one or more 'U' slots in the SIW structure have been proposed in [7], [8-9]. Different types of the SIW filters for Ku band applications have been proposed in [10], [11] are difficult to fabricate due to their complex structures. Though number of research works have been carried out to improve the SIW filter performance to make it suitable for Ku band applications of satellite communication, however there are ample scopes to improve it with respect to compactness, high isolation, low-cost production, minimum group delay, etc.

In this paper, the basic SIW filter is modified by using tapered vias and multiple 'U' slots to obtain a compact and easily fabricable SIW bandpass filter for Ku band applications (12 GHz to 17 GHz) with reduced group delay and better isolation. The proposed filter designed and simulated on a low cost FR4 substrate by the high frequency structure simulator (HFSS) v14. The improvements in results are obtained for the proposed filter as compared to the similar designs available in the literature. It provides better confidence on performance parameters of the proposed SIW filter.

II. SIW FILTER DESIGN

A. *Theory of SIW Filter*

The SIW structure is based on planar dielectric substrates with top and bottom layers perforated with arrays of metalized via holes. A basic structure of an SIW consists of the top and bottom metal planes of a substrate and two parallel arrays of via holes (also known as via fence) integrated in the substrate as shown in Fig. 1.The width of the SIW structure is calculated by using Eq. 1 corresponding to the lower cutoff frequency 'f_{cutoff}' for the dominant mode (TE_{10}) as given in [8].

$$\mathrm{f_{cutoff}} = \frac{\mathrm{c}}{2l\sqrt{\epsilon_\mathrm{r}}} \tag{1}$$

where design parameter 'l' is the effective width between the two arrays of vias, 'ϵ_r' is the dielectric constant of the substrate used for the construction of SIW structure, 'c' is the velocity of light in free space.

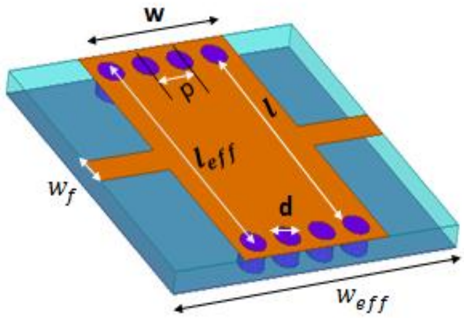

Fig. 1. Basic structure of SIW filter

Two parallel arrays of via holes in the substrate of the SIW structure are used to realize the bilateral edge walls of the SIW filter in a miniature scale [5]. Increase in spacing 'p' between the adjacent via holes leads to increase in leakage loss of the SIW structure and also increase in the diameter 'd' of the via hole creates the loss. Hence, the selection of location and diameter of the via holes in the SIW structure are crucial design parameters. The design parameters of array of vias are optimistically calculated by using Eq. 2-3 as in [5].

$$\mathrm{d} < \frac{\lambda_g}{5} \qquad (2)$$

$$p \leq 2d \qquad (3)$$

where 'λ_g' is the guided wavelength and is determined by using Eq. 4.

$$\lambda_g = \frac{\lambda_{ms}}{\sqrt{\epsilon_{r_{eff}}}} \qquad (4)$$

Here, 'λ_{ms}' is the wavelength of the microstrip patch corresponding to centre frequency 'f_c' of the bandpass filter and '$\epsilon_{r_{eff}}$' is the effective dielectric constant as in [12]. 'f_c' is calculated using Eq. 5.

$$f_c = \frac{f_l + f_h}{2} \qquad (5)$$

where 'f_l' and 'f_h' are the lower and upper cut-off frequencies of the SIW bandpass filter.

B. Design of Tapered Via Transition

A wideband transition from microstrip line to SIW structure, consists of a microstrip along two extra vias are designed as proposed in [6] and is shown in Fig. 3. The effective width of the waveguide port 'l' [6] is calculated by using Eq. 6.

$$l = \frac{c}{2\, f_{cutoff} \sqrt{\epsilon_r}} \qquad (6)$$

The feedline i.e. transition from microstrip line having an impedance of 50 Ohm to SIW structure having impedance less than 50 Ohm is tapered out in order to minimize the reflection loss to a greater extends. Two metallic vias are designed at the transition of tapered microstrip line to SIW structure to achieve a wide band of operation. The physical dimensions of taper, i.e. length 'l_{tap}' and width 'w_{tap}' are calculated using the analytical expressions given in [6].

C. Design of U slot structure

A 'U' slot is created in the SIW structure as shown in Fig. 3 to achieve a better resonance and better stop band behavior in the upper stop band region, i.e. due to the introduction of 'U' slot, the SIW filter exhibits a comparatively sharp transition from passband to stopband [7]. The 'U' slot introduces a stopband zero and hence the stopband behavior improves. The size of the 'U' slot is determined by using Eq. 7 as given in [7].

$$f_z = \frac{c}{4\, l_s \sqrt{\epsilon_r}} \qquad (7)$$

where 'l_s' is the length of U slot and 'f_z' is the frequency at which zero has to be introduced. The number of transmission zeros will be equal to the number of U- shape slots and also equal to number of resonances in the passband [7].

D. Design of proposed SIW filter

The design of the proposed SIW bandpass filter follows the design flow as shown in Fig. 2.

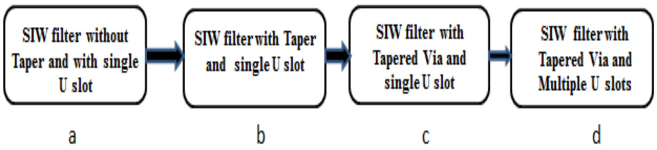

Fig. 2. Design Flow of Proposed Antenna

a. Basic Design
b. Improved Design-I
c. Improved Design-II
d. Final Design

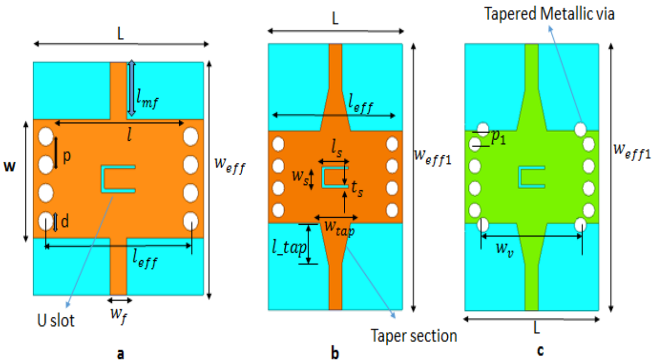

Fig. 3. Geometries of the designed SIW Filters

a. Top view of the Basic Design
b. Top view of the Improved Design-I
c. Top view of the Improved Design-II

The geometry of the various designed filters, i.e. a, b, c are shown in the Fig. 3. The SIW filter proposed in [7] is taken as the basic design in our design. In basic design, due to the presence of single 'U' shape slot, the stopband performance is improved as the 'U' slot introduces a transmission zero in the stopband. The basic design filter has less bandwidth and low S_{11} performance due to impedance mismatching. With improved design-I, a tapered transition which provides a smooth transition from microstrip line to SIW structure is introduced to enhance the S_{11} performance and bandwidth [6]. Further, Improved design-II is the modified version of improved design-I with two vias at the transition of microstrip line to SIW. Further, S_{11} performance is improved due to presence of two extra vias. Eventually, in the final design, improved design-II is modified with the addition of four numbers of ‘U’ slots arranged in two parallel rows as shown in Fig. 4. Due to the presence of multiple ‘U’ slots, the upper stopband performance increases.

The SIW filters are designed on a double-sided copper clad FR4 (relative dielectric constant 4.4, substrate thickness 0.5 mm, loss tangent 0.02 S/m) substrate due to its easy availability & low cost. The basic dimensions of the SIW filters are initially calculated for Ku band (12 GHz- 18 GHz) by using the design equations as given in Eq. 1-7. These parameters are further fine-tuned using parametric analysis and inbuilt optimizer present in HFSS v.14. The final design parameters of all the designed SIW filters are given in TABLE I.

TABLE I. DESIGN PARAMETERS OF THE PROPOSED SIW FILTERS

Design parameters (in mm)	**Basic Design**	**Improved Design I**	**Improved Design II**	**Final Design**
W	5.66	5.66	5.66	5.66
w_{eff}	11.12	--	--	--
l	7.59	7.59	7.59	7.59
l_{eff}	8.49	8.49	8.49	8.49
L	9.99	9.99	9.99	9.99
p	1.35	1.35	1.35	1.35
d	0.9	0.9	0.9	0.9
l_{mf}	2.73	2.73	2.73	2.73
w_f	0.955	0.955	0.955	0.955
w_{eff1}	--	16.3	16.3	16.3
l_{tap}	--	2.59	2.59	2.59
w_{tap}	--	2.264	2.264	2.264
l_s	1.98	1.98	1.98	1.98
t_s	1.32	1.32	1.32	1.32
w_s	0.1887	0.1887	0.1887	0.1887
p_1	--	0.885	0.885	0.885
w_v	--	7.26	7.26	7.26
g	--	--	--	0.6
m	--	--	--	6.465
s_1	--	--	--	0.528

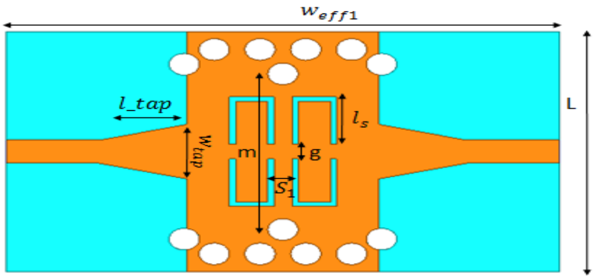

Fig. 4. Geometry of the designed SIW Filter (final design)

III. SIMULATION RESULTS & DISCUSSION

A comprehensive analysis of simulation results are presented in this section.

A. *Simulation Results*

Design and simulation of the proposed SIW filter are carried out rigorously so that the fabricated filter will meet the requirements for Ku band applications. The simulated results for various filter performance parameters are discussed in the following sections.

1) *S_{11} performance:* The S_{11} performances are as shown in Fig. 5. The results show that for the basic design, the passband is not wide enough to accommodate the Ku band frequencies as the S_{11} curve for a band of frequencies in the passband region go above the -10 dB reference level. This is basically due to the sharp transition in the impedance level of the microstrip feedline to the SIW structure. So, this problem is reduced in improved design-I, by using a tapered out transition between microstrip feedline and SIW structure. As the tapered transition provides a smooth transition, the complete passpand (9.3 GHz - 17.2 GHz) is achieved in improved design-I. Further, in improved design-II, two metallic vias are introduced between tapered microstrip line and SIW structure for the smooth transition from the planar structure to waveguide structure with minimal level of reflection. This results in further improvement in the return loss of the filter as maximum S_{11} value attained is -44 dB. The final design provides a better S_{11} value of -53.14 dB at the frequency of 14.5 GHz due to the introduction of multiple ‘U’ slots as shown in Fig. 6.

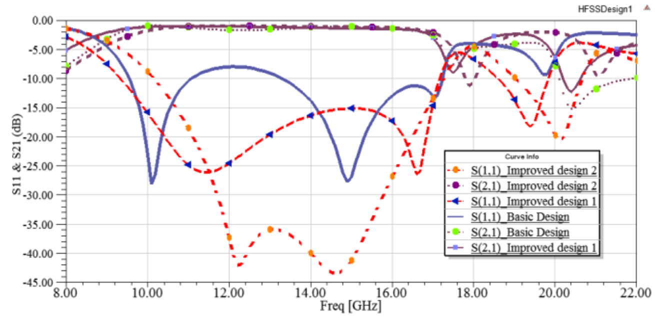

Fig. 5. S_{11} and S_{21} plots of basic design, improved design-I and improved design-II

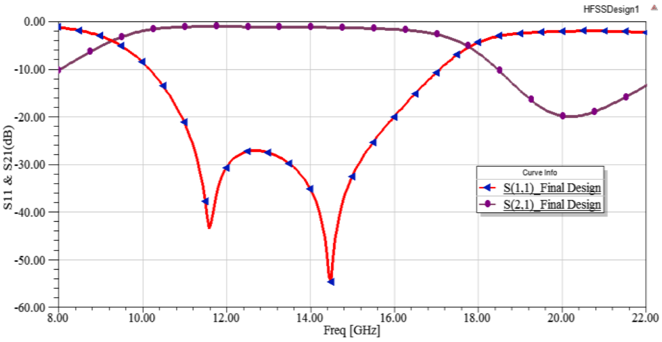

Fig. 6. S_{11} and S_{21} plots of the final design

2) *S_{21} performance:* Insertion loss plots are as shown in Fig. 5. The results show that the insertion loss remains below 2 dB in the passband region for all the first three designs. However, the stopband responses of these designs are not good enough due to absence of stopband zero. Finally, the stopband response of the final design is improved significantly as shown in Fig. 6. This is achieved by the introduction of four numbers of 'U' shape slots arranged in two parallel arrays in the SIW structure which introduce a transmission zero in the upper stopband and hence the insertion loss attains its maximum value of 20 dB at a frequency of 20 GHz.

3) *Group Delay:* The proposed design attains a maximum group delay of 0.24 ns and minimum delay of 0.16 ns throughout the passband as shown in Fig. 7. This indicates that during this duration, the phase behavior of the signal remains linear.

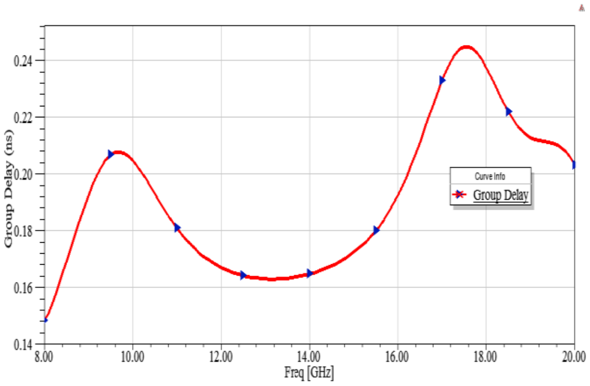

Fig. 7. Group delay curve of the final design

4) *Radiation Loss:* Radiation loss which is resulted due to the lossy nature of the substrate used in the design and is calculated by using $1-|S_{11}|^2 - |S_{21}|^2$ as given in [8]. The radiation loss plotted Vs frequency is shown in Fig. 8. It shows that the radiation loss is below 20% for the passband of the proposed filter. This can be further reduced by using low loss substrates such as Roger RO4350, etc.

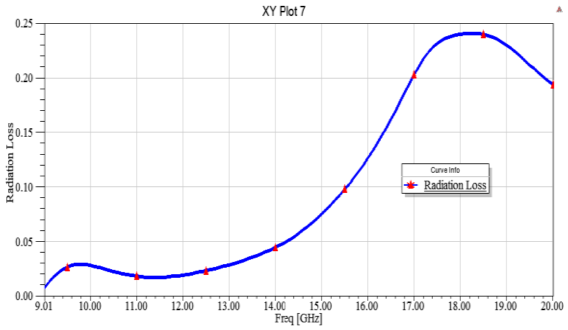

Fig. 8. Radiation loss of the final design

B. *Discussion*

The simulation results are summarized in the TABLE II. However, it indicates that the final proposed design possesses the improved performance parameters such as low reflection, better isolation, the minimum value of group delay and radiation loss. Hence, the proposed filter can be suitably used for the Ku-band applications.

The simulated results are compared with the simulation results of existing SIW filters for Ku band applications in literature as presented in TABLE III. The proposed SIW filter shows a good amount of improvement as compared to the performances of SIW filters reported in literatures.

TABLE II. SIMULATED PERFORMANCE PARAMETERS OF THE PROPOSED SIW FILTERS

Result Analysis	**Basic Design**	**Improved Design I**	**Improved Design II**	**Final Design**
f_L *(GHz)*	9.55	9.30	10	10.19
f_H *(GHz)*	17.22	17.22	17.22	17.05
S_{11} *(in dB)*	< -8	<-10	<-10	<-10
S_{11} *(in dB) (Best case)*	-26	-25.74	-43	-54
S_{21} *(in dB)*	> -4.20	> -2.40	> -2.25	> -2.20

TABLE III. COMPARISON OF PERFORMANCE OF PROPOSED SIW FILTER WITH OTHER SIW FILTERS FOR KU- BAND APPLICATIONS

Design proposed by	**Substrate**	**Insertion Loss (dB)**	**Return loss (dB)**	**3dB FBW (%)**	**Footprint (mm^2)**	**f_c (Center Freq.) (GHz)**
[10]	KYOCERA A493	1.4	>10	10	545	12.6
[11]	RO4 350	1	>5	23	1915	15.75
Proposed Design	FR4	1.13	>10	51	160	13.5

IV. CONCLUSIONS

A compact and improved wideband band pass filter with a smooth planar to SIW transition having multiple 'U' shaped slots is proposed for the Ku band applications. The proposed filter possesses better stop band characteristics due to the presence of multiple 'U' shaped slots in the SIW structure which introduces transmission zeros in the upper stopband. The taper transition with two metallic vias at the planar to SIW transition reduces the reflection which results in wideband operation of the filter. The overall size of the filter is 160 mm^2 which shows its compactness. The proposed design possesses low reflection, better isolation, better fractional bandwidth (FBW) of 51%, compactness, low cost and ease of fabrication as compared to the traditional filters for Ku band application.

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