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A compact SIW bandpass filter using DMS-DGS structures for Ku-band applications

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Abstract. This paper presents a design of compact SIW (substrate integrated waveguide) bandpass filter for application in Ku-band Transmit up-convert frequency (i.e., 13.7–14.1 GHz) used for satellite communications. Based on Defected Microstrip Structure-Defected Ground Structure combination (DMS-DGS), this SIW filter structure is designed to improve passband and stopband performance. By merging circular ring slot (CRS) with interdigital DGS, better passband characteristics with sharp stopband attenuation are obtained. To validate the design, the filter is fabricated using Rogers substrate. The size measures 23.8 mm × 10 mm and operates at a center frequency of 13.9 GHz. Measured results of the filter agree well with the simulated results. Also, designed BPF filter has advantage of low insertion loss, better return loss, compact size and high stopband rejection.

Keywords. Bandpass filter (BPF); defected ground structure (DGS); defected microstrip structure (DMS); substrate integrated waveguide (SIW); Ku-band.

1. Introduction

Rectangular waveguides are used for transmitting signals between system modules with lower losses at high-frequency applications. Further, rectangular waveguides are huge and bulky. The technology gap between rectangular waveguides and other planar circuits is filled up by SIW (Substrate Integrated Waveguide). This has the benefit of mere integration into substrates and planar waveguide circuits specifically Printed Circuit Board process (PCB) and also SIW has the benefit of low-cost, low loss, compact and better quality factor.

Literature has been reviewed for similar structures. Filter design for uplink path in Ku-band Up-Converter Block (BUC) is designed by traditional coupled waveguide cavities and different coupled line filter topologies [1]. A new SIW structure with better out of band rejection using a hollow substrate integrated coaxial line is reported [2]. However, the return loss is comparatively low. Hence, one side via hole SIW technique called Half-Mode Substrate Integrated Waveguide (HMSIW) is reported [3] to exhibit wide stopband, but the circuit size is extremely large. Circuit minimization can be achieved by another most important technique called Defected Ground Structure (DGS) has gained attractive attention among all other techniques to improve band-stop performance and to suppress higher order harmonics [4–6]. SIW filter utilizing Complementary Split Ring Resonator (CSRRs) structure, which controls the passband of the filter over the dimensions of the split ring resonator is introduced [7, 8] with lower return loss. Among these a typical DMS introduced in this paper exhibits slow wave properties, rejecting microwaves at certain frequencies. In [9–11], the DGS and DMS combination provides sharp cut-off, wide rejection bandwidth and good filtering response. Nevertheless, the stopband attenuation has to be improved.

In this work, a new compact SIW BPF is analyzed that uses DMS-DGS technique. First, the DMS unit is introduced by etching two vertical slots or defects on the top metal layer. This exhibits slow-wave characteristics, finite passband and excellent stopband attenuation. Furthermore, the upper stop band performance is enhanced by cascading interdigital DGS with a circular ring slot on the bottom metal layer. The proposed SIW BPF presented here provides better filtering performance by comparing with the other cited existing filter.

2. Ku-band Tx-filter

Figure 1 shows block diagram of the Ku-band transceiver up-converter path. Crosstalk between the Tx-band (13.75–14.5 GHz) and Rx-band (10.95–12.75 GHz) can be eliminated by the transmit filter in uplink path.

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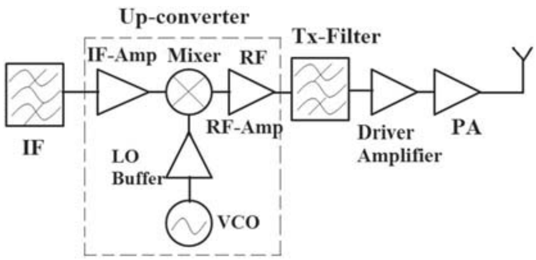


Figure 1. Ku-band transceiver up-converter block.

3. Design and development of DGS-DMS based SIW BPF

3.1 *Design of full mode SIW BPF*

Conventional SIW BPF is designed by an array of metalized via holes arranged on two rows of the top and bottom plane of the SIW cavity. This is connecting the dielectric substrate. The layout of the SIW filter structure is shown in figure 2(a). It consists of SIW cavity and a microstrip transmission line. The microstrip line width is designed to match characteristic impedance of 50 Ω. Figure 2(b) illustrates the frequency response of the SIW filter structure. It provides high pass filtering characteristics. Hence, the bandpass filter response could be obtained by implementing the concept of DMS and DGS. The geometrical specifications of designed filter are d- via hole diameter, P- distance between center to the center via on both row, W_{SIW} - width of SIW, W_{eff} - effective width of SIW, L_{SIW} - length of the SIW and L_{eff} - effective length of SIW.

The mathematical equation for calculating effective width and length are given by,

$$W_{eff} = W_{SIW} - \frac{d^2}{0.95p} \tag{1}$$

$$L_{eff} = L_{SIW} - \frac{d^2}{0.95p} \tag{2}$$

Depending on effective width of the SIW, designed filter cutoff frequency can be calculated by following equation,

$$f_c = \frac{c}{2w_{SIW}\sqrt{\varepsilon_r}} \tag{3}$$

where 'c' stands for velocity of electromagnetic waves and $\varepsilon_r$is relative dielectric constant. To avoid leakage loss for via post in SIW cavity side walls, filter should satisfy following conditions, $d/p > 0.5$, $d/W_{SIW} < 0.4$. For SIW cavity, at TE_{m0n} resonant mode, required resonant frequency can be driven by using the given equation,

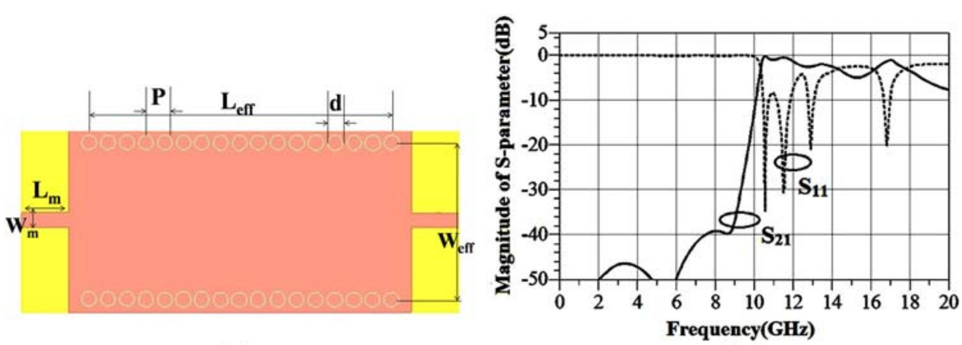
$$f_{m0n} = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{w_{eff}}\right)^2 + \left(\frac{n}{l_{eff}}\right)^2} \tag{4}$$

3.2 *Design of SIW BPF with DMS*

Figure 3(a) shows the layout of SIW BPF with two vertical slots etched on the top conducting layer to disturb the electromagnetic flow of energy to minimize the circuit area and hence the entire volume can be reduced. The slot dimensions are further optimized to introduce bandpass behavior with lower and upper stopband. The simulated frequency response is outlined in figure 3(b) with passband centered at 16.5 GHz and also unwanted spurious response excited at 11.5 GHz. Additionally, it provides passband but with poor return loss, insertion loss and upper stopband characteristics.

3.3 *Design of proposed SIW BPF using DMS and DGS for Ku-band Tx-filter applications*

Figure 4 shows layout of the proposed SIW BPF and its transmission response is shown in figure 5. In figure 4, it can be seen that the brown part is the top metal plane and yellow part is the bottom ground plane. Hence the frequency response of the filter with DMS is not sufficient, so



(a) (b)

Figure 2. (**a**) Structure of SIW filter (without DMS and DGS), (**b**) simulated S-parameter of the SIW filter. The filter dimensions are L_{eff} = 16.5 mm, W_{eff} = 8.6 mm, L_m = 2.5 mm, W = 0.8 mm, P = 1 mm, d = 0.82 mm.

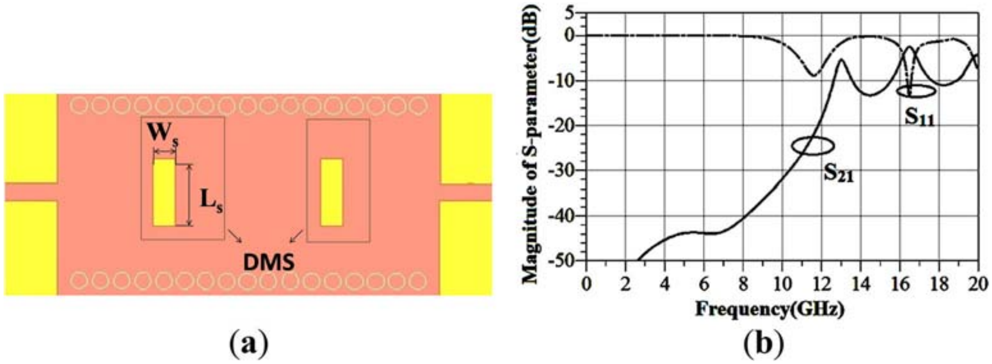


Figure 3. (**a**) Layout of the proposed SIW BPF with DMS, (**b**) simulated S-parameter of filter with DMS. The slot dimensions are W_s = 1.08 mm, L_s = 3.2 mm.

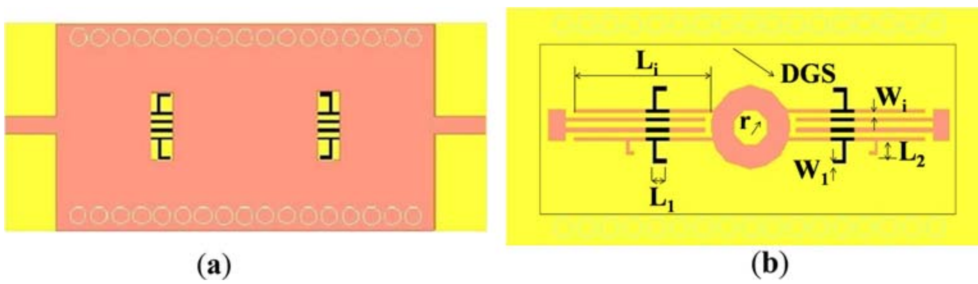


Figure 4. Layout of the proposed SIW BPF (with DMS and DGS). (**a**) top view, (**b**) bottom view.

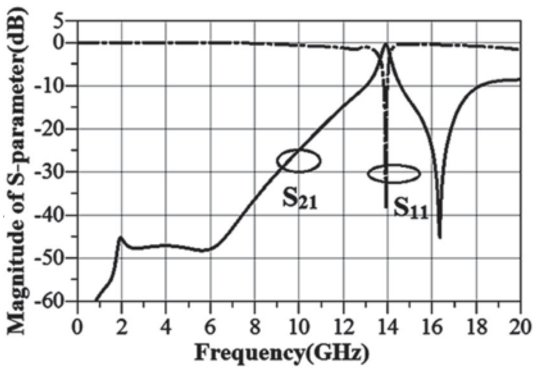


Figure 5. Simulated S-parameter of the proposed SIW BPF.

the DGS technique is employed to enhance the filter characteristics.

DGS is accomplished by defecting or etching a desired shape in bottom ground plane of SIW cavity structure. Depending on DGS slot dimensions, shielded current dispersion in bottom metallic layer is modified. This leads to Controlled excitation and the electromagnetic waves that propagate through the substrate layer. It composed of circular ring resonator defected on center of the bottom plane to produce the upper stopband and to eliminate the spurious response. Further the interdigital DGS lines coupled to the circular ring resonator can exhibits the narrow passband characteristics with return loss > 20 dB. In order to realize the filter bandwidth, three pairs of L-slots are incorporated on the top of interdigital lines to improve frequency selectivity, out of band rejection with lower insertion loss. The optimized DGS dimensions are L_i = 6.1 mm, W_{i} = 0.19 mm, L_1 = 0.62 mm, W_1 = 0.22 mm, L_2 = 0.56 mm.

DMS equivalent circuit model is shown in figure 6(a). The etched or defected surface corresponds to capacitance while the arms represent inductance. The mechanical behavior of the DMS is that two vertical slots, which acts as a shunt resonator. The frequency response between circuit and EM simulation are in good agreement and demonstrated in figure 6(b).

The LC equivalent circuit of DGS is shown in figure 7(a). Here the capacitance C_d indicates the circular ring slot at center connected in series with $2C_d$, which represents two interdigital slot lines and third $2C_d$ represents three pairs of L-slots. The S-parameters of circuit and EM simulation are compared and plotted in figure 7(B). The value of L_d and C_d are calculated using

$$C_{\mathrm{d}} = \frac{5f_{\mathrm{c}}}{\pi\left(f_0^2 - f_{\mathrm{c}}^2\right)} \tag{5}$$

$$L_{\mathrm{d}} = \frac{250}{\pi^2 f_0^2 c_{\mathrm{d}}} \tag{6}$$

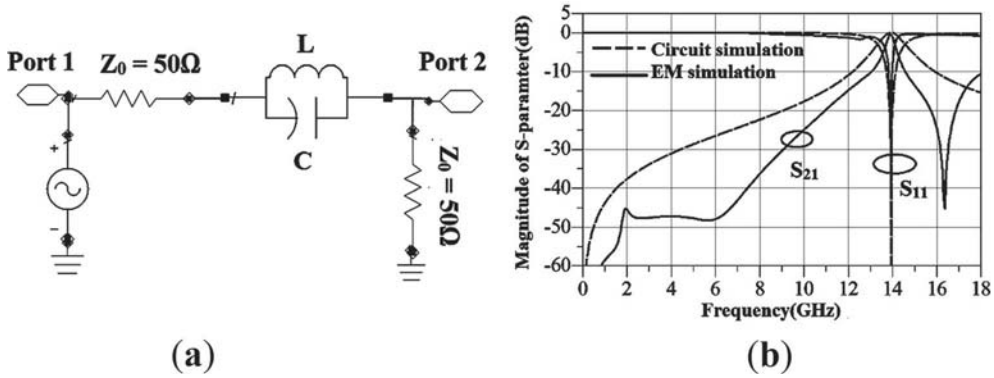


Figure 6. (**a**) Equivalent circuit model of DMS unit, (**b**) comparative results.

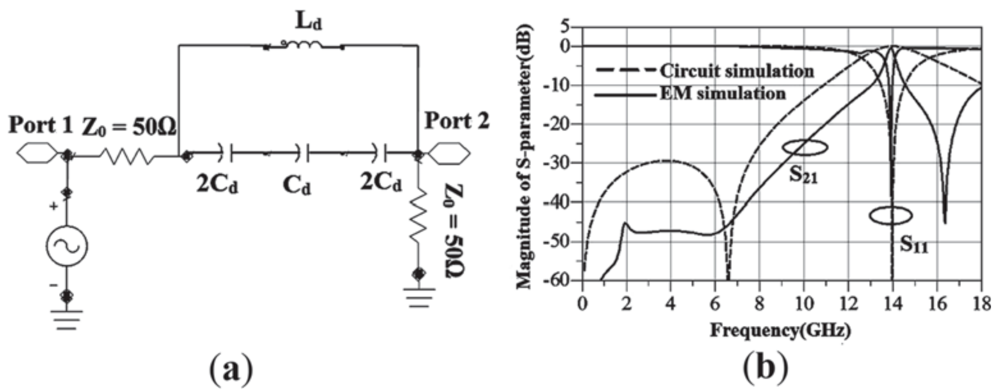


Figure 7. (**a**) Equivalent circuit model of DGS unit, (**b**) comparison between circuit and EM simulation.

where f_0 and f_c are the resonant and cut-off frequency of the stopband, respectively.

4. Fabrication and measured results

SMA connectors used for the boards are Amphenol connectors manufactured to suit up to 18 GHz measurements. The filter is fabricated using Rogers RO3035 substrate with ε_r = 3.5 and substrate thickness of 0.5 mm. Figure 8 compares both simulated and measured responses of the filter. Simulation was done using advanced design system software and measurement was done using Agilent network analyzer respectively. The response deviation between simulation and measurements is mainly caused by fabrication tolerances, material and SMA connector losses.

Table 1 gives the performance comparison of the proposed filter with other works.

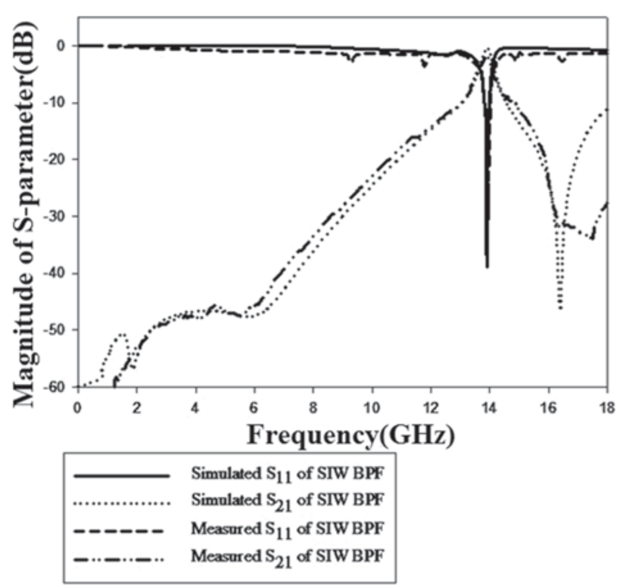


Figure 8. Comparative results of measured and simulation.

Table 1. Performance comparison.

References	f_0 (GHz)	FBW (%)	IL (dB)	RL (dB)	Effective size λg × λg	Upper stopband attenuation	Isolation (dB)	Isolation band
Maassen *et al* (2016) [1]	14.1	14.8	1.5	20	(0.10 × 0.6)	−20 dB@28 GHz	> 15	26∼28 GHz
	14.2	9.7	2.2	17	(0.7 × 0.25)	−10 dB@27 GHz	> 35	25∼27 GHz
	14	11.2	1.9	10	(0.3 × 0.3)	−42 dB@29.7 GHz	> 35	16∼29 GHz
Zhang *et al* (2016) [3]	5	7.6	1.7	> 20	0.5 × 0.21	−20 dB@5.4–20.1 GHz	> 30	9∼21.2 GHz
Zhang *et al* (2005) [6]	5.8	5.10	1.38	25	1.64 × 1.64	−30 dB@8 GHz	> 25	7.2∼8 GHz
Zhang *et al* (2018) [7]	7.89/8.89	8.8/10.1	1.5/1.9	15/14	0.85 × 0.87	−19 dB@9.6 GHz	> 35	9.3∼10 GHz
This work	13.9	3.5	1.8	35	0.024 × 0.013	> −28 dB@17.9 GHz	> 30	16.2∼17.5 GHz

5. Conclusion

In this paper, compact SIW BPF is designed based on DMS-DGS technique. This topology provides good filtering response that demonstrates the strong suppression of undesired harmonics in the filter structure. Thus, overall dimension of the filter is reduced and filter miniaturization can be attained. Eventually, the proposed filter works at a frequency range of 13.6 GHz–14.1 GHz centered at 13.9 GHz with FBW of 3.5%. In comparison with the other conventional SIW filter structures, this DMS-DGS SIW BPF structure has the advantage of compact size, low insertion loss of < 2 dB, deep return loss of 35 dB, and high out of band rejection of 30 dB at 16 GHz.

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