Miniaturized Substrate-Integrated Waveguide Bandpass Filter Using Symmetric Vertical Slots

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Abstract

A substrate-integrated waveguide (SIW) bandpass filter designed by introducing a vertical slot in the central metallic septum of the SIW is proposed in this paper. The input/output arrangement analysis and the stub variation in the port termination are also demonstrated, resulting in a wider bandwidth and better performance characteristics. The SIW bandpass filter (BPF) has a passband in the range of 18.23 GHz - 28.74 GHz depending on the stub variation arrangement with the central symmetric slot synthesized on a 0.5 mm thick planar RO 3003 substrate using a periodically arranged metal via holes. The proposed filter has excellent wide stopband rejection characteristics of -16 dB from 30 GHz to 40 GHz. Furthermore, the experimentally measured S-parameters of the filter are in good agreement with the simulated results; thus, the performance of the filter is validated.

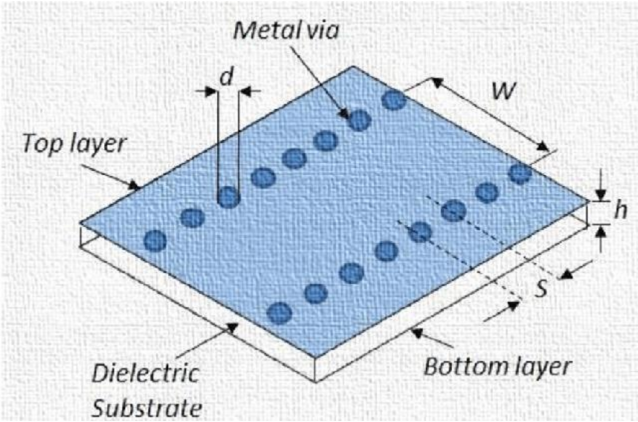
Keywords: Stopband Rejection, Bandpass Filter, S-Parameters, Symmetric Slots, Substrate- Integrated Waveguide

1. Introduction

The development of miniaturized, wideband, and enhanced microwave and millimeter wave systems for extensive variety of applications in higher frequency ranges and bands, particularly the X, Ku, and K bands, has become increasingly important. Microstrip lines and radio frequency (RF) waveguides were the dominant transmission lines until the late twentieth century. However, microstrip line-based circuits/components suffer from ineffectiveness at extreme frequencies, and require challenging fabrication processes in the implementation of RF, microwave, and millimeter-wave components due to their shorter wavelengths. Additionally, waveguide devices are not cost-effective, are difficult to fabricate, and are difficult to integrate with other planar components. Substrate-Integrated Waveguides (SIWs) were recently developed at the beginning of the 21st century for the design of efficient circuits and components. It has emerged as an alternative technology to design components with the benefits of both microstrip and rectangular waveguides as a cost-effective solution with reduced radiation losses, increased quality (Q) factor and power handling capacity, minimum group delay and ease of integration with other planar components.

The SIW transmission line is essentially a dielectric-filled waveguide implemented by two lines of conducting posts, aka vias, implanted within a dielectric substrate, and electrically connecting the top and bottom conducting layer walls, typically as shown in Figure 1 [1]. The concept of an SIW bandpass filter was first proposed by Deslandes and Wu and later by others [2-4] where the integration of microstrips and rectangular waveguides in planar form, the integrated transition of coplanar waveguide to rectangular waveguide and the single-substrate integration technique of planar circuits and waveguide filters were proposed. In the recent decades, it has developed as a promising technology for many microwave, terahertz and millimeter wave-based applications.

Figure 1: Geometry of a Substrate-Integrated Waveguide



The latest developments in wireless communication systems mandate bandpass filters (BPFs) with the requirements of compact size, wideband, low insertion loss, high selectivity and wide out-of-band rejection capabilities. Microstrip BPFs are generally implemented by conjoining a low-pass filter and a high-pass filter using the low-pass to bandpass transformation, or the insertion loss (IL) technique or by employing multiple resonators [5]. A vialess compact BPF using metamaterials was designed in [6, 7] to obtain a large fractional bandwidth (FBW) and small insertion loss. The resonant frequency is obtained through split circular rings and a rectangular stub in [6] and a composite right-left handed transmission line (CRLH-TL) in [7].

Since the SIW behaves as a bridge between planar and nonplanar transmission lines, it exhibits the advantages of both metallic waveguides and planar structures. Nonplanar rectangular or circular waveguides can handle high power and provide high selectivity, but are more and is relatively expensive. Planar transmission lines are lightweight at low-cost for mass production but cannot withstand high power and generally have greater losses. Literature on SIW filters, such as cross-coupled filters, defected ground structure (DGS)-based filters, metamaterial-based filters, tunable filters and filters on new materials, along with bandwidth enhancement, size reduction and selectivity improvement has also been published [8]. In SIW technology, BPFs are usually fabricated by using multiple coupled resonators or introducing low-pass structures such as metamaterials, electromagnetic bandgap (EBG) structures, and multimode resonators (MMRs). Metamaterials are used in the design of SIW filters to achieve miniaturization and enhanced selectivity. EBG structures are incorporated in SIW to design millimeter-wave and superwide BPFs with the advantage of wide out-of-band rejection. EBGs, along with folded SIW (FSIW) and half-mode T septum SIW (HMTSSIW), are used to achieve significant size reduction and larger bandwidths but with high ILs. Quasi-elliptic filters are designed using SIW by utilizing slot coupling and cross coupling with the benefit of a low IL [5].

The construction of an SIW filter between 8 GHz and 40 GHz is made possible, but has a strong advantage for high-frequency bands. Appropriate materials with a dissipation factor as low as 0.0009 at 10 GHz are chosen for the SIW filter. Hence, it has a high Q factor and very low insertion loss. In the case of ceramic and LC filters, it is not easy to apply frequency ranges over 10 GHz, but SIW filters are available up to 40 GHz to generate a broad bandwidth. Compared with cavity or waveguide filters, surface-mounted and connectorized SIW materials are small in size and inexpensive, exhibit high performance and can endure high power (up to 50 W).

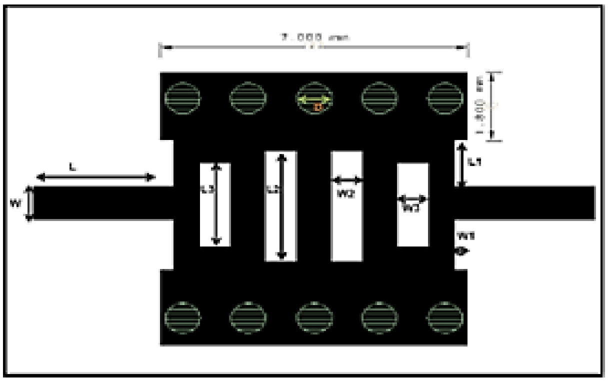
In this paper, a novel method is proposed for the design of compact substrate-integrated waveguide bandpass filters using symmetric vertical slots specifically for applications in K-band frequencies ranging from 18 GHz to 30 GHz. The resonant passband is achieved in the single-layer SIW bandpass filter structure with the help of symmetric vertical slots. Furthermore, the parametric stub variations are examined to suppress the spurious radiation levels in the stopband. A better reflection coefficient, minimal group delay, and a broad rejection level at the stopband are achieved by the proposed filter design. The comparison of the external quality factor (Qe) and coupling coefficient (K) with the observed stub dimension variation is then used to present an additional configuration. Advanced design system (ADS) software was used to simulate the SIW structures to validate the experimental measurements.

The design of the proposed substrate-integrated waveguide based bandpass filter is provided in section 2 along with its proposed layout and pattern of surface current density. The simulation results of the scattering parameters, quality factor and group delay are furnished by employing the advanced design system (ADS) software in section 3. The scattering and other important parameters of the fabricated miniaturized SIW-BPF in the laboratory setup are described in section 4. These parameters are discussed and compared with published results available in the literature. Section 5 includes the concluding remarks.

2. Design of the SIW Bandpass Filter

Although SIW filters with a number of design techniques and topologies have been presented in many studies, they follow some conciliations in choosing critical design specifications to prioritize size, selectivity, power handling capability, quality factor, cost, sensitivity to environmental effects, and other in-band and out-band performance metrics [9]. It is difficult to achieve all these conflicting design requirements simultaneously. This would require the use of additional resonators and modifications of the conventional substrate integration waveguide filter. In particular, the width of the SIW bandpass filter significantly affects the cutoff frequency. The various geometric parameters of the SIW filter design as defined in [10] are: the diameter of the via (d), spacing between the via holes (p), physical waveguide width (WSIW), waveguide length (LSIW), length of the microstrip line (L), width of the microstrip line (W), stub Length (L) and stub width (W). Figure 2 shows the layout of the proposed SIW bandpass filter. Waveguide transmission and resonant mode excitation may be observed in the vertical slots of the SIW bandpass filter construction where strong coupling is primarily evident.

Figure 2: Proposed Layout of the Full-mode SIW-BPF



With reference to the investigations of [5], the passband resonant frequency can be expressed as:

$$f_0 = \frac{c_0}{2\varepsilon_r}\sqrt{\left(\frac{1}{W_1}\right)^2 + \left(\frac{1}{L_1}\right)^2} \quad (1)$$

where W1 and L1 represent the width and length of the microstrip line, respectively, and are calculated using the following equations:

$$W_1 = W_{SIW} - \frac{d^2}{0.95\ p} \quad (2)$$

$$L_1 = L_{SIW} - \frac{d^2}{0.95\ p} \quad (3)$$

where WSIW and LSIW represent the parameters of the SIW bandpass filter structure. The spacing between the via holes, the via diameter, and the width of the SIW structure are adjusted such that the leakage losses from the waveguide are negligible. The fundamental parameters of the metallic via, namely, the via diameter (d) and the spacing between the vias (p), are denoted by the following equations, as given in [6]:

$$d < \lambda_g/5 \quad (4)$$

and

$$p < 2d \quad (5)$$

where λg is the guided wavelength.

3. Simulation Results

The proposed SIW structure is simulated using Advanced Design System (ADS) software, and various key parameters are measured for a given specification of the material properties and dimensions. The parameters, namely, the transmission coefficient, coupling coefficient, external quality factor and group delay response, of the proposed SIW high-pass filter are emphasized. The simulation output of the transmission coefficient of the SIW bandpass filter with varying slot length and width is shown in Figure 3. The transmission coefficient $|S21|$ in dB was obtained for three different sets of L1 (1 mm, 2 mm and 3 mm) and W1 (0.1 mm, 0.2 mm and 0.3 mm) values. Increases in the width and length of the stub line result in coupling at the passband's resonance frequency as well as enhanced rejection in the stopband. When the length L1 and width W1 are optimized to 1.3 mm and 0.3 mm, respectively, good matching qualities in the passband are observed. For simulation purposes, a Roger substrate material with a thickness of 0.5 mm and a relative permittivity of 3.5 is considered.

Figure 3: Simulated Transmission Coefficient $|S21|$ of the Proposed SIW Bandpass Filter Configuration with Variations in the Length (L1) and Width (W1) Parameters

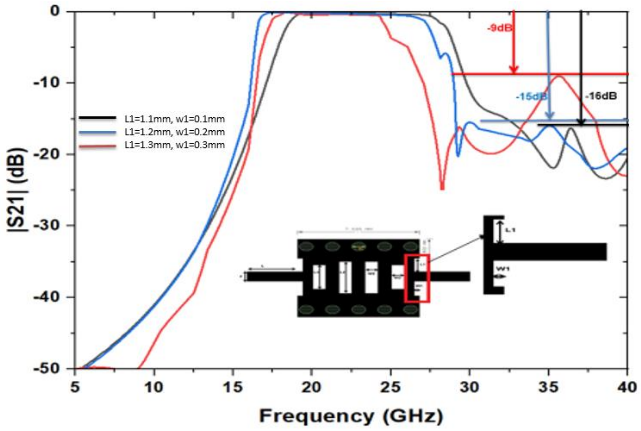
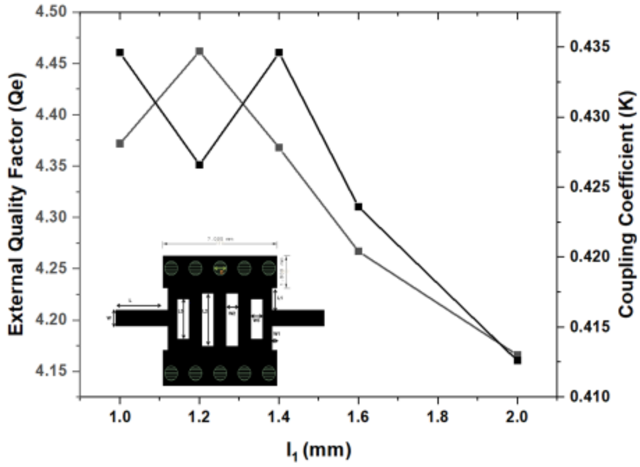


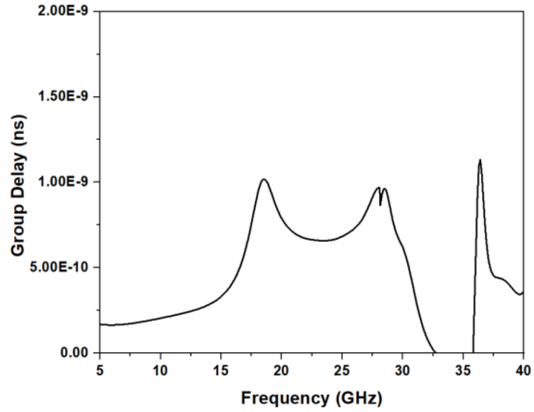
Figure 4 shows a comparison of the coupling coefficient (K) and the external quality factor (Qe) with respect to the physical dimension (L1) of the bandpass filter. By adjusting the transmission length of the vertical slots, high magnitudes of the quality factor, Qe, and coupling coefficient, K, are observed. The slot dimensions are the primary determinant of the coupling effect in the passband, and changes in the slot dimensions result in reduced spurious levels in the stopband. Moreover, the substrate thickness has a major impact on the quality factor. The dimensions of the filter are shown in Figure 1 are considered to be: L = 2.8, L1 = 1.2, L2 = 2.9, L3 = 2.2, W = 0.9, W1 = 0.3, W2 = 0.7 and W3 = 0.6 (all measurements are in mm). In the figure, the curve connecting the lightly shaded square points represents the variation in the external quality factor with respect to the SIW parameter L1. For example, for L1 = 1 mm, Qe ≈ 4.37. The curve connecting the darkly shaded square points corresponds to the variation in the coupling coefficient K against the SIW parameter L1. As an example, for L1 = 1 mm, K ≈ 4.46.

Figure 4: Simulated Response of the External Quality Factor and the Coupling Coefficient versus the Distance of the Vertical Slot for the Proposed SIW Bandpass Filter



The simulated group delay over the passband frequency range is illustrated in Figure 5 for the proposed SIW filter. The maximum and minimum group delays obtained with the simulated structure are 0.9 ns and 0.6 ns, respectively, over the designed pass band frequency range. The following are the structural parameters for the proposed SIW BPFs: the hole or via diameter is 0.8 mm, and there is a 1.5 mm distance between the two holes.

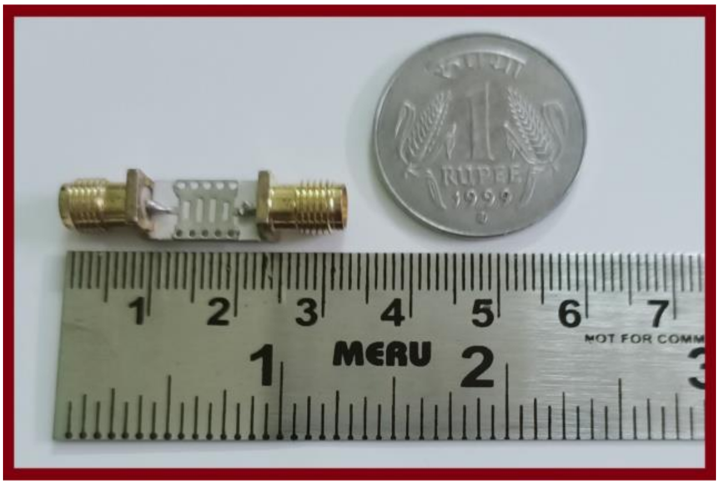
Figure 5: Simulated Group Delay Response of the SIW Bandpass Filter



4. Experimental Results and Discussion

The proposed substrate-integrated waveguide structure is fabricated for bandpass filter applications on a 0.5 mm thick planar RO 3003 substrate using a periodically arranged metal via holes to exhibit a passband in the range from 18.23 GHz to 28.74 GHz. The structure also possesses a suitable stub variation arrangement with the central symmetric slot synthesized on the given substrate. A photograph of the fabricated SIW structure is shown in Figure 6. The typical dimensions of the bandpass filter employed are: L = 2.8, L1 = 1.2, L2 = 2.9, L3 = 2.2, W = 0.9, W1 = 0.3, W2 = 0.7, and W3 = 0.6, all measured in mm and are the same as those used in the simulation. The variation in the stub dimension can be used to achieve a wide range of spurious suppression at the stopband. The overall size of the proposed SIW bandpass filter is 12.7 mm by 7 mm.

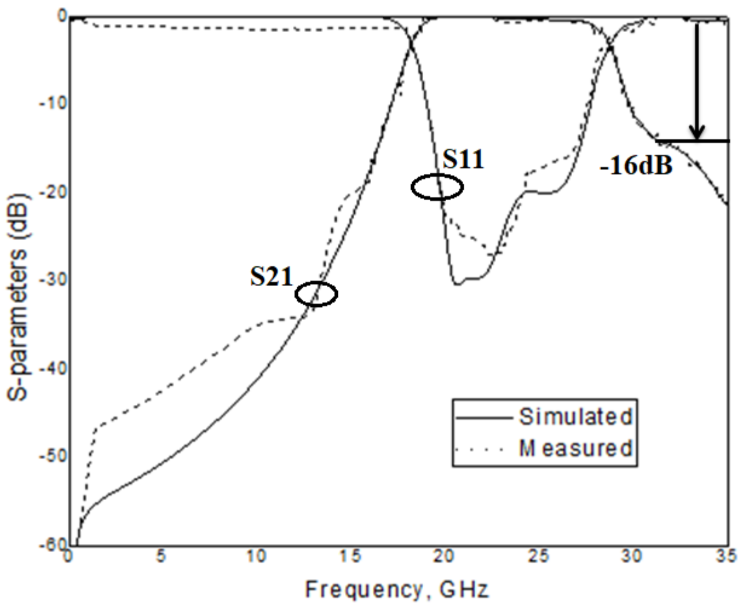
Figure 6: Photograph of the Proposed SIW Bandpass Filter



The reflection and transmission coefficient of the proposed filter configuration with stub length (L1) and width (W1) variations are shown in the frequency response figure 7. Passband characteristics are observed with the vertical slot coupling loaded in the SIW structure. The slots also affect the magnitude of the spurious rejection level and the selectivity in the upper stopband. The passband reflection coefficient S11 ranges from 18.2 GHz to 24.74 GHz. For frequencies of 30 GHz, spur level suppression is observed, and the simulated in-band insertion loss S21 is less than -0.5 dB with a rejection level of -16 dB.

It is also observed that the passband frequency ranges from 18.2 GHz to 28.74 GHz at - 3 dB and from 19.07 GHz to 27.67 GHz at -10 dB with a fractional bandwidth of 44.73%. The measured filter passband is observed at 23.45 GHz with passband frequencies ranging from 18.2 GHz to 24.74 GHz at – 3 dB. The insertion loss (IL) S21 is less than 1 dB, whereas the maximum in-band return loss (RL) S11 is more than 20 dB over the passband. The stopband rejection level of the SIW bandpass filter is measured at -16 dB for frequencies between 30 GHz and 35 GHz. This demonstrates that the increased selectivity of the SIW bandpass filter was designed. The figure also shows the transmission and reflection coefficients corresponding to both the simulated (solid curve) and experimental measurements (dashed curve).

Figure 7: Simulated and Measured Frequency Response of the SIW Bandpass Filter



A detailed comparison of their performances with those of other recently reported SIW bandpass filters with almost similar features is provided in Table 1. The results demonstrate that the proposed SIW bandpass filter provides comparatively good parameter values such as higher frequency selectivity, lower insertion loss, compact size, and better stopband rejection. The frequency range of 18-28 GHz often has applications in the uplink and downlink of mobile satellite communications. Another major advantage is its highly miniaturized compact size of 12.7 mm x 7 mm, which is quite useful for the manufacture of reduced size devices.

Ref.	Passband frequency range (GHz)	Centre frequency (GHz)	Return loss (dB)	Insertion loss (dB)	FBW (%)	Rejection band (GHz)	Size (mm)

[13]	9.172-20.31	16	> 17.6	< 1.5	76	23 - 40	19.6 x 12.56
[12]	14.35- 16.76	14.5 - 19.2	> 18	> 1.5	20.8	20 - 30	27 x 11.5 x 3.2
[11]	9.5 – 16.46	13	> 14	1.1	48	16.7 - 24	15.37 x 15.37
Proposed work	18.2 - 28.74	23.45	> 20	< 0.5	35	30 - 35	12.7 x 7

Table 1: Comparison of the Simulated and Measured Features of the Proposed SIW Bandpass Filter

5. Conclusion

In this paper, an SIW bandpass filter is designed to operate in the passband frequency range of 18.23 GHz - 28.74 GHz depending on the stub variation arrangement with a central symmetric slot synthesized on a 0.5 mm thick planar RO 3003 substrate using a periodically arranged metal via holes, and its performance is investigated experimentally and further validated by using Advanced Design System (ADS) software. The designed filter has significant performance, better stopband rejection, compact size, and lower insertion loss with a miniaturized size of 12.7 mm x7 mm. It can be effectively integrated with other planar circuits to lower costs, based on the simulation and measurement results.

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