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A Substrate Integrated Waveguide Based Filtenna for X and Ku Band Application

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Abstract: In this paper Substrate Integrated Waveguide-based filtenna operating at Ku band is proposed. The model is designed on a low loss dielectric substrate having a thickness of 0.508 mm and comprises of shorting vias along two edges of the substrate walls. To realize a bandpass filter, secondary shorting vias are placed close to primary shorting vias. The dimension and position of the vias are carefully analyzed for Ku band frequencies. The model is fabricated on Roger RT/duroid 5880 and the performance characteristics are measured. The proposed model achieves significant impedance characteristics with wider bandwidth in the Ku band. The model also achieves a maximum gain of 7.46 dBi in the operating band thus making it suitable for Ku-band applications. Substrate Integrated Waveguide (SIW) Structures possess most of the advantages over conventional radio-frequency waveguides since they have high power management capacity with self-consistent electrical shielding. The most noteworthy advantage of SIW, it can able to integrate all the components on the same substrate, both passive and active components.

Keywords: Antenna radiation patterns; filtenna; microstrip patch; rectangular waveguide; substrate integrates waveguide; transverse electric modes; transverse magnetic modes

1 Introduction

Due to the increase in demand for multifunctional antennas in wireless communications, the size of the antenna profile is greatly reduced and also provides better feasibility in integration with high-frequency circuits. Recently filtenna becomes popular since the Radio Frequency (RF) space is occupied with much of the available spectrum and hence the role of the filter along with the Antenna becomes crucial. The substrate integrated waveguide (SIW) has proven to be a good choice because of its modular integration and low cost [1]. Most of the literature discusses the design of filter and antenna separately and are coupled with a 50 Ω impedance matching circuit which consumes much space in the antenna profile. At higher frequencies in GHz, the transmission and radiation losses are more in microstrip or coplanar waveguide [2]. This can be replaced by placing a single filtenna design which reduces the overall antenna profile and also eliminates the need for an additional 50 Ω impedance matching circuit, also SIW takes advantage of planar antennas which constitutes low profile, less weight low, low cost for fabrication of such antenna [3]. The utilization of both SIW technology along filtenna further improves the antenna profile size and also improves the ease of fabrication and integration. SIW structures exhibit propagating characteristics Identical to most metallic waveguides because the metallic holes are closely spaced and leakage due to radiation can be neglected. SIW holds good of modes of the rectangular waveguides, namely TE modes with $n = 1$; 2; SIW will not support Transverse Magnetic Waves (TM) modes. In particular, the fundamental mode is similar to the Transverse Electric Waves (TE) mode of rectangular waveguide, with vertical electric current density on the side walls. Owing to this similarity between SIW and rectangular waveguide, empirical relations have been obtained between the geometrical dimension of the SIW and the effective width of the rectangular waveguide with the same propagation characteristics. SIW technology is used by many researchers to increase the gain and directivity of antenna which may be used by many applications. The electromagnetic signals are guided to the radiating patch, placed beyond the microstrip line in the die-electric substrate. Due to this launching of signals the gain increases also helps in narrowing the radiation pattern and thereby increasing directivity. The radiation slots, which are created above and below the center axis of the rectangular patch separated by half of the wavelength, are used to achieve good impedance matching, uniform excitation throughout the field, and suppression of grating lobes [4]. A compact SIW based filtenna comprising of the parasitic patch is proposed. At the operating band, the longitudinal slots on the surface, function like a Perfect electric conductor, and hence antenna radiates traditionally whereas at the interference band these act like perfect magnetic conductor stops propagation at the cavity [5]. The model utilized a half-mode substrate-integrated rectangular cavity to reduce its overall antenna size.

2 Related Work

SIW technology is used by many researchers to increase the gain and directivity of antenna which may be used by many applications. The electromagnetic signals are guided to the radiating patch, placed beyond the microstrip line in the die-electric substrate. Due to this launching of signals the gain increases also helps in narrowing the radiation pattern and thereby increasing directivity [6]. The radiation slots, which are created above and below the center axis of the rectangular patch separated by half of the wavelength, are used to achieve good impedance matching, uniform excitation throughout the field, and suppression of grating lobes. At the operating band, the longitudinal slots on the surface, function like a Perfect electric conductor, and hence antenna radiates traditionally whereas at the interference band these act like perfect magnetic conductor stops propagation at the cavity [7].

A SIW based filtenna with reconfigurable nulls using electric and magnetic coupling structure is demonstrated [8]. Filtenna can also be designed by utilizing the synthesis of filter structures by placing vertical cavities as in [9]. Similarly, the filtenna can also be realized by placing three vertical cavities integrated to achieve a wider Average Final Body Weight (FBW) ratio. However, an increasing number of filter cavities to improve FBW results in wider profile thickness.

A low profile SIW-based filtenna is reported [10] with improved bandwidth characteristics that utilize a Complementary Split-Ring Resonator (CSRR) over the SIW structures. The tapered transforms the quasi-TEM mode in the microstrip line into the TE 10 mode in the SIW. Since the electric fields of the two dissimilar structures are approximately oriented in the same direction, the microstrip line is well suited to excite the Substrate Integrated Waveguide (SIW). To combine the SIW technology with microstrip we need a microstrip transition. This transition is like a tapered structure as microstrip lines have 50 Ω impedance to match with the integrated waveguide.

In this paper, a SIW based filtenna with improved bandwidth and radiation characteristics is proposed. The antenna is modeled on a low-cost roger substrate with a profile thickness of 1.6 mm which makes it feasible for the integration of other High-frequency circuits. The antenna is analyzed and is fabricated to measure its performance characteristics and are compared with other conventional models.

3 Substrate Integrated Waveguide Geometry

The dielectric-filled metallic waveguide can be realized using substrate integrate waveguide [11] which exhibits similar propagation characteristics. The design of the proposed antenna is as shown in Fig. 1. The width 'W' of SIW is calculated from center to center distance between the rows of vias. Each via by spacing 'p' and has radius 'r'. The length of die electric layer 'L'. Let a, b denote the width and height of the conventional rectangular waveguide respectively. Assuming a > b, the propagating mode with the lowest cut-off frequency is TE 10 (dominant model). We calculate using

$$a = \frac{C}{2f_{cio}\sqrt{\varepsilon_r}} \tag{1}$$

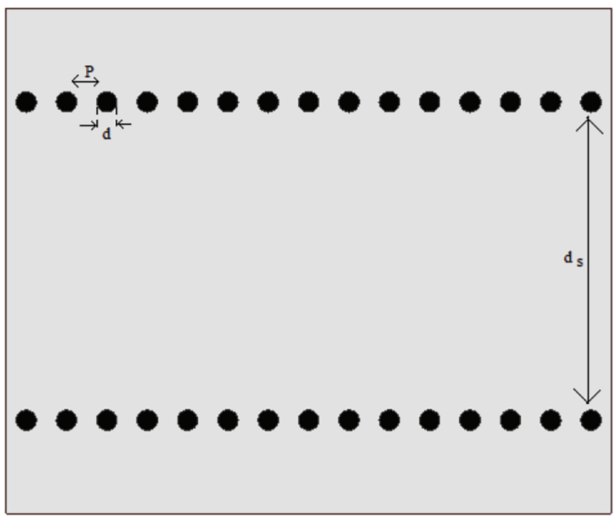

Figure 1: SIW geometry

The cutoff frequency of each propagating mode

$$f_{cmm} = \frac{C}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{a}\right)^2} \tag{2}$$

where c is the speed of light in vacuum, m, n are mode numbers, a, b are dimensions of the waveguide. For TE_{10} mode, the cutoff frequency is given as $f_c = \frac{c}{2a}$. For substrate integrated waveguide the dimension d_s is the distance between the SIW walls and is given by $d_s = a_d + \frac{d^2}{0.95p}$ where $a_d = \frac{a}{\sqrt{\varepsilon_r}}$ d is the diameter of via and p (p must satisfy $p < 2$d) is the distance between the vias. The guided wavelength is calculated from $\lambda_g = \frac{2\pi}{\sqrt{\frac{\varepsilon_r(2\pi f)^2}{c^2} - \left(\frac{\pi}{a}\right)^2}}$ and d must satisfy $d < \frac{\lambda_g}{5}$.

Based on the design equations, the geometry of the substrate integrated waveguide along with two slot geometry is shown in Figs. 1 and 2. The slots are created on either side of the axis horizontally. The slot antenna is simply an opening cut in the conductor sheet. It has long-distance communication, gives enhanced impedance with space, and has higher mechanical stability concerning dipole antenna. Slots perfectly conductor to E-field. The filter is constructed by placing vias below the primary vias of the SIW waveguide. These will act as bandpass filters which allow 16 GHz frequency to pass through.

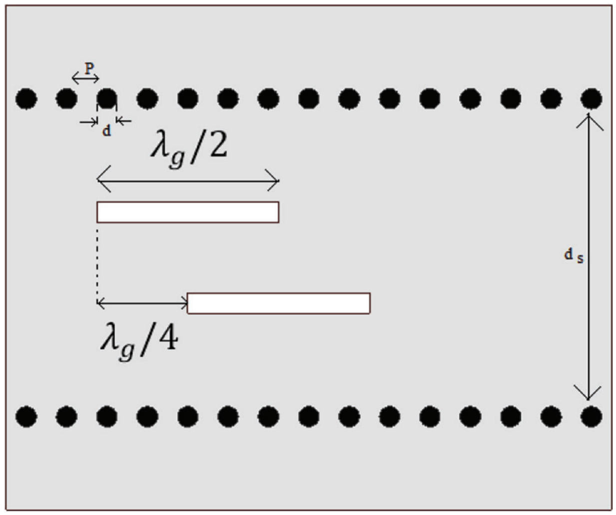

Figure 2: Two slot SIW geometry

The surface current distribution over the geometry is shown in Fig. 3. The surface current distribution exhibits sinusoidal variation in the variations of the field on the surface of the structure and is confined with the SIW walls above its operating frequency. The generation of Electric and Magnetic field (E-field and H-field) are noted and also it is understood that SIW works under TE10 dominant mode where E-fields is transverse to the direction of propagation and has no longitudinal electric field is present. Also discussed the Microstrip transition which is used to excite signals on SIW. Microstrip transition is used to obtain perfect impedance matching so that maximum standing wave can be avoided.

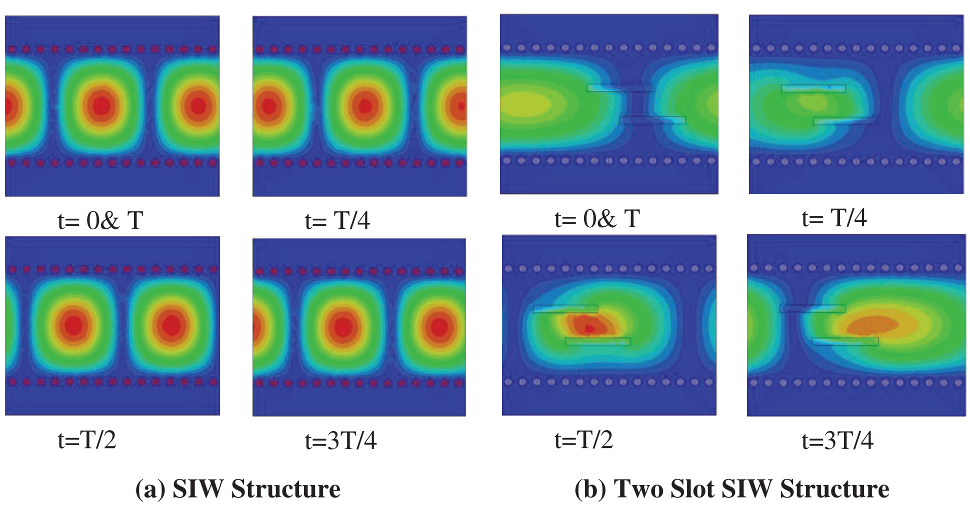

Figure 3: Surface current distribution

The dominant mode TE10 exists within the waveguide. Each slot could be independently fed with a voltage source across the slot. But this would be very difficult to construct, and This is not possible in practice. Instead, the waveguide is used as the transmission line to feed the elements. The position, shape, and orientation of the slots will determine how (or if) they radiate. In addition, the shape of the waveguide and frequency of operation will play a major role.

The antenna is modeled on Roger (RTduroid 5880tm) having a relative permittivity of 2.2 and thickness of 1.6 mm. The −10 dB reflection coefficient curve corresponding to both SIW with and without slot geometry is given in Fig. 4. The structure achieves −10 dB impedance characteristics over its entire operating X band which comprises of 8 to 12 GHz with a cutoff frequency of 6.5 GHz.

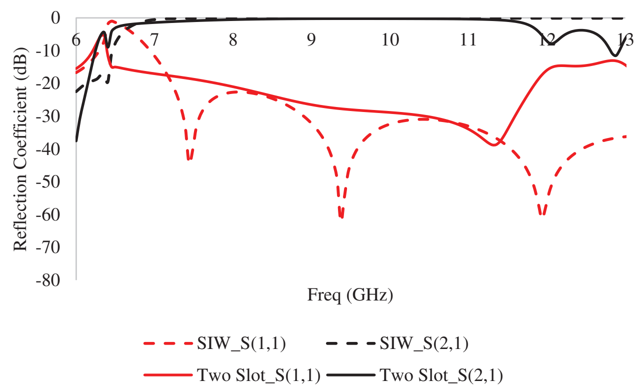

Figure 4: Reflection coefficient (dB)

The phase constant β corresponding to the fundamental TE10 mode for given slotted substrate integrated waveguide is given by

$$\beta = \sqrt{k_0^2 \pm \left(\frac{\pi}{a}\right)^2} < k_0 \tag{3}$$

where k_0 is the wavenumber. Fig. 5 shows the normalized phase constant $\left(\frac{\beta}{k_0}\right)$ corresponding to substrate integrated waveguide compared with slotted SIW structure. It is observed that the structure attains a real phase value whose mode propagates above the cutoff frequency of 6.5 GHz.

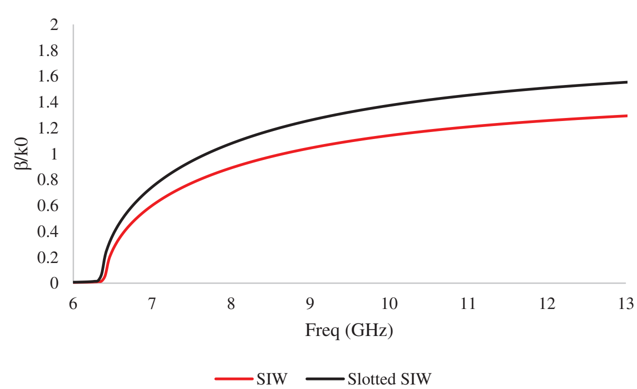

Figure 5: Normalized phase constant $\left(\frac{\beta}{k_0}\right)$

The attenuation constant α is given by

$$\alpha = -\frac{1}{2L}\ln\left(|S_{11}|^2 + |S_{21}|^2\right) \tag{4}$$

where L is the aperture length. Fig. 6 shows the normalized attenuation characteristics of the substrate integrated waveguide compared with the slotted SIW structure. It is inferred that the structure attains minimum attenuation at its operating band. The dispersion characteristics of the antenna are determined from the phase constant and attenuation constant of the proposed SIW structure.

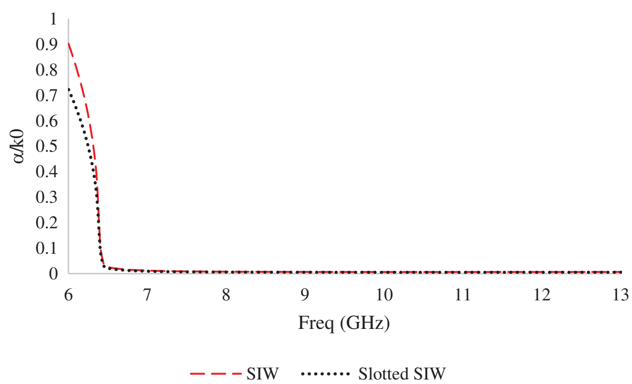

Figure 6: Normalized attenuation constant $\left(\frac{\alpha}{k_0}\right)$

3.1 Higher-Order Inductive Based Filter Design

A higher-order inductive filter is proposed as shown in Fig. 7. The filter comprises metallic vias placed to provide an inductive window having a width of $W_i (i \in 1, 2)$ and length of the cavity resonators are given by $2p$ as shown in Fig. 7.

The filter is resonating at

$$F_{101} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{\pi}{W_i}\right)^2 + \left(\frac{\pi}{L_i}\right)^2} \tag{5}$$

where $L_i = 2 * p$

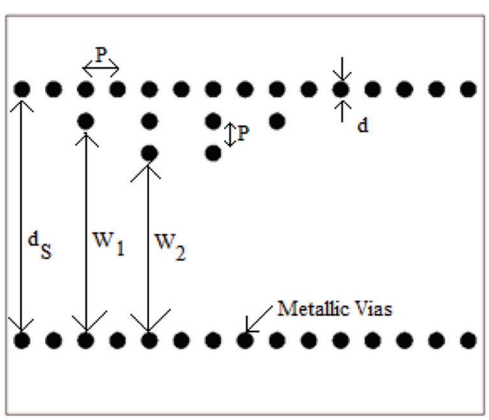

Figure 7: Higher-order inductive filter

4 SIW Based Filtenna

The proposed antenna geometry is integrating both Substrate integrated waveguide and filtenna as shown in Fig. 8. The model utilizes a micro strip to SIW transition [12] connected to a 50 Ω micro stirp line and integrated with SIW. The width and length of the tapered section are designed and optimized for impedance matching.

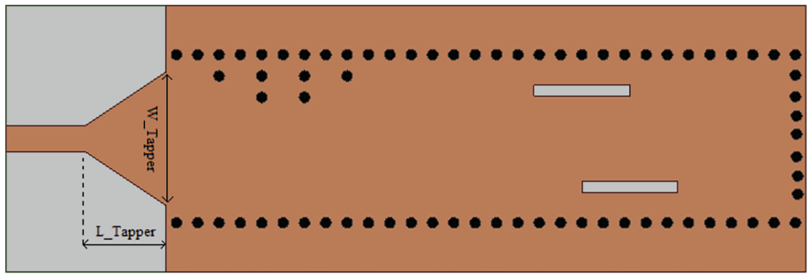

Figure 8: Proposed SIW based filtenna

The antenna is fabricated on a low-cost roger substrate having a relative permittivity of 2.2 and a thickness of 1.6 mm. The model is connected with a 50 Ω Sub-Miniature version A (SMA) connector. To validate the performance characteristics of the antenna model, the performances of the prototype are measured and are compared with simulated results. Microstrip to SIW transition, based on a simple and straightforward tapered transition [13]. The tapered microstrip line section is connected to a 50 microstrip line and integrated with SIW. The width and length of the tapered section are designed and optimized to achieve the minimization of S11 [14].

The waveguide _filters are formed with resonator distributed demands interconnected by admittance. The equivalent circuit contains impedance in vertex and phase shifter. In the SIW bandpass filter, phase shifting is happened by shifting the position of the via in the x-axis i.e., by changing the width of the filter [15].

The impedance characteristics of the filtenna for both simulated and measured results are shown in Fig. 9. The reflection coefficient curve corresponding to filtenna geometry achieves −10 dB impedance characteristics over its entire operating X band which comprises of 8 to 12 GHz with sharp roll-off around its operating band. The radiation characteristics of the antenna are measured by three-antenna gain methods and the gain of the proposed model is calculated using the Friss transmission equation given below

$$P_r = G_t G_r P_t \left(\frac{\lambda}{4\pi r}\right)^2 \quad (6)$$

The SIW antenna was stimulated in HFSS, considering both dielectric and metallic losses. The stimulated antenna is tested anechoic chamber, Chennai. During antenna measurements co-axial-to-microstrip transition used, it is connected with polycarbonate holder. The distance between transmitting and receiving antenna in Transmitting and receiving antenna in an anechoic chamber is 2 mts.

The simulated and measured radiation characteristics of the antenna model are shown in Fig. 10. The antenna achieves asymmetrical radiation pattern with a peak gain of 7.18 dBi for simulated and 6.94 dBi for measured at its resonant frequency.

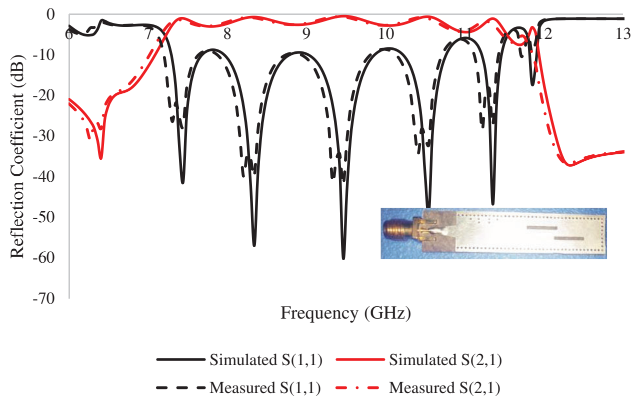

Figure 9: Impedance characteristics of filter design

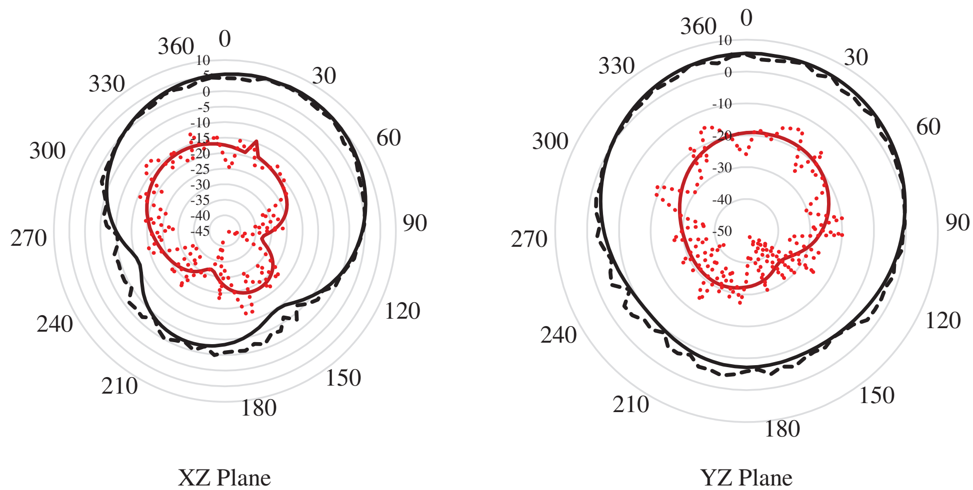

Figure 10: Radiation characteristics

The microstrip transitions are made for the perfect launch of EM waves on the surface of the antenna. SMA connector is terminated at end of the patch which provides 50 Ω impedance thereby providing coaxial coupling. No slots on the surface can be increased to get better bandwidth and efficiency which may be considered to be extended work. The results obtained show a good agreement between measured and simulated results. Although this antenna is designed at microwave frequencies, it shows an alterative for 5G applications.

5 Conclusion

This paper was presented with the design and experimentally one assured performance of Ku band SIW filtenna and is compatible with microwave technology. At each stage the SIW antenna is simulated and results are plotted. Two slots are made on the surface of SIW to increase the radiation capacity of the antenna. The bandpass filter is constructed on the surface by placing extra vias near SIW cylindrical vias placed on a patch which helps to achieve a better filtering response of the antenna.

A compact SIW based filtenna operating at Ku band frequencies is proposed. The model utilizes a filter section integrated with SIW based slotted section. The microstrip to taper transition is used for impedance matching and is terminated with a 50 Ω transmission line. The model is analyzed for dispersion characteristics and is fabricated on a low cost substrate. The prototype attains resonates at 16 GHz in the Ku band region with a peak gain of 7.18 dBi for simulated and 6.94 dBi for measured at its resonant frequency.

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