Design of a CPW Fed Substrate integrated waveguide using Frequency selective surface

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Abstract

Substrate integrated waveguide (SIW) technology makes it possible to realize an entire circuit including a transition, planar circuitry, waveguide components and devices in a single printed circuit board. In this paper, a new approach to design a SIW using frequency selective surfaces (FSS) been analyzed. An accurate analytical modelling is applied to compute the propagation constant and the cut-off frequency of SIW structure. The structure has fed with modified grounded coplanar waveguide (GCPW) feed to reduce the propagation losses. Finally, a comparison has been made on the propagation properties of both SIW and SIW based on FSS.

Keywords— frequency selective surfaces, grounded CPW millimetre wave circuits, substrate integrated waveguides (SIW).

I. Introduction

SIW technique makes it feasible to design a complete circuit including planar circuitry. The guided wave and mode characteristics of a SIW for the first time reported using the analytical method and analytical modelling of SIW from rectangular waveguide besides reporting ohmic losses is reported later. Moreover, its propagation constant and cut-off frequency were analyzed and compared with measured results [1-2]. A closed form empirical relation to calculate dispersion characteristics of SIW using the transmission matrix method is described [3]. Dispersion characters of SIW were explained by the BI-RME method and proved that SIW and equivalent rectangular waveguide have the same characteristics [4]. However, the transition from microstrip to RWG in planar form plays an important role in wave propagation from different types of structures. The experiment is being carried out to study the transition of microstrip line to RWG in a planar form which is integrated on the same dielectric substrate. The results showed a better than -0.3 dB insertion loss and 12% effective bandwidth as well as the losses in a SIW circuit discontinuous structure, such as H-plane step, post resonator and a 90° bend using a rectangular waveguide approach also been reported [5]. Until recently, a new approach of designing SIW using a simple square loop FSS was proposed by upholding EM wave propagation characteristics and dimensions of the conventional SIW [6].

In the present paper, design of SIW for X-band application is carried by incorporating FSS element on the PEC wall as a perfect reflecting wall. Since FSS is a good reflector and it can resemble the same characteristics of a conventional SIW. Furthermore, frequency tuning is possible using FSS as a side wall which is impossible in case of the PEC side wall. The FSS can also result in the stealth application which is more desirable for radar systems and the bulk waveguide antennas can be replaced with FSS. The design approach and results are presented briefly in subsequent sections.

II. Design of SIW Structure using FSS

SIW structure incorporated with FSS element along its longitudinal direction of length *L* is presented in Fig. 1(a). The metallic vias with a diameter *d* are placed along the longitudinal direction, with a separation of *P* on a dielectric substrate of thickness *t*, will act as a side wall, topology resembles a dielectric filled rectangular waveguide. The centre to centre distance of a vias (*Wsiw)* is the width of SIW. The separation between two vias W_{eq} is equivalent to the width of rectangular waveguide. *EM* wave propagates through the SIW structure by reflecting from the lower and upper PEC walls. The same functionality can be incurred by using an FSS element by employing it as a reflector in the frequency range of interested. United States frequency allocations between 7.9 GHz to 12.2GHz. However, the X band frequency allocations run from 8GHz to 12GHz.

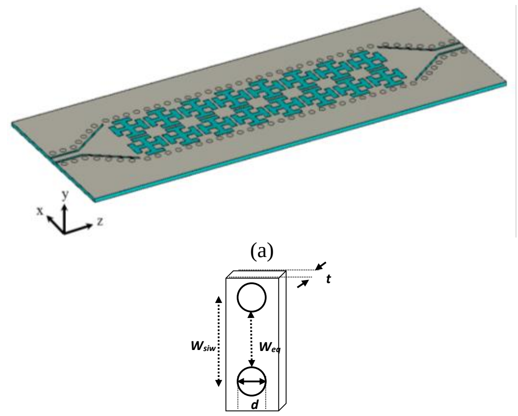


Figure 1 Structural representation of SIW: (a) 3-D view of CPW fed SIW with Jerusalem cross FSS, (b) Unit cell of SIW.

A. Working principle

It is well known that an FSS layer has its adverse applications as a sub-reflector, transmitter and absorber in industrial commercial and aerospace. In this paper, an FSS element is used as a PEC wall which is employed as a high impedance surface to reflect the EM wave impingements. The FSS element resonance frequency should be allocated a minimum of twice do not upset the behaviour of conventional SIW [6]. A Jerusalem cross (JC) FSS element has been chosen for facilitating the bandpass filter response. The unit cell is presented As a result, it has a dominant resonance frequency response in the range of interest. Initial dimensions of FSS element are determined from equations given [7]. An equivalent circuit model has been adopted to design the FSS unit cell element [8].

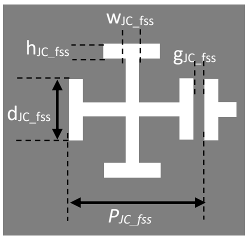


Figure 2 FSS unit cell of Jerusalem cross FSS element.

In Fig. 2, P_{JC_fss} = 5.0 mm, d_{JC_fss} = 2.55 mm, h_{JC_fss} = 0.8 mm, w_{JC_fss} = 0.8 mm and g_{jc_fss} = 0.4 mm. FSS elements are analyzed on a dielectric substrate of thickness t = 0.508 mm with dielectric constant $\varepsilon_r = 4.3$.

B. Dispersion characteristics

Two adverse circles of a unit cell in SIW structure are shown in Fig. 3, topology further can be approximately modelled as two half sections of rectangular waveguides cascaded with different width of W_1 and W_2. The first half section consists of two-half circles which construct a rectangular waveguide with a width of W_1 = W_{eq} (i.e. W_{siw}-d) and length of L_1 = d, on a constant dielectric substrate thickness of t.

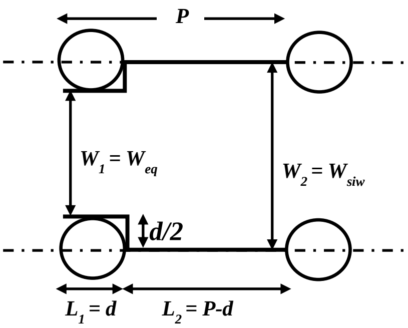


Figure 3 Unit cell topology of SIW structure.

The second half section is a rectangular waveguide with a width of W_2 = W_{siw} *and* length of L_2 = P-d, on the same dielectric substrate. The *ABCD* parameters of modelled rectangular waveguide are given by the Equation 1:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos(\beta_m l_m) & \frac{j\omega\mu}{\beta_m}\sin(\beta_m l_m) \\ \frac{j\beta_m}{\omega\mu}\sin(\beta_m l_m) & \cos(\beta_m l_m) \end{bmatrix} \quad (1)$$

In above expression β_m, l_m corresponds to the propagation constant and length of the equivalent waveguide. The entire *ABCD* matrix of the unit cell given in Equation 1 can be represented as a product of transmission matrices of half sections. By applying the Floquet theorem and after analytical simplification, the equation of propagation constant (β) of SIW is:

$$\beta = \frac{1}{P}\cos^{-1}\left(\frac{A+D}{2}\right) \quad (2)$$

The computed complex propagation constant using Equation 2 against frequency is plotted in Fig. 4. The effective width of SIW is calculated using Equation 3:

$$W_{eff} \cong \frac{W_{siw}}{\sqrt{1+\left(\frac{2W_{siw}-d}{P}\right)\left(\frac{d}{W_{siw}-d}\right)^2}} \quad (3)$$

Here, W_{eff} is the effective width of equivalent RWG, W_{siw} is the width of SIW, and P and d are the spacing between two vias and diameter of the SIW structure respectively. The RWG and SIW are designed to operate at *X-band* and their passband starts from 6.55 GHz (cutoff frequency of *X-band*) is same for both structures with designed SIW dimensions. The propagation constant of SIW and SIW with FSS top wall have been computed using analytical formulas and compared in Fig. 4. From the figure, it is evident that the propagation characteristics are same for both structures.

C. Cut off frequency of SIW

The cutoff frequency of SIW is determined by using dispersion characteristics. The frequency response *w.r.to*

equivalent width of SIW is computed for both fundamental mode (TE_{10}) and second higher order mode (TE_{20}) by varying vias diameter (D mm) with P at *1.55* mm which is determined by the initial conditions is shown in Fig. 5. For more accurate modelling, a parametric study has been carried out *w.r.to* design parameters d and P. The curves are approximated by Equation 4(a) and 4(b) which are obtained using the least square's method:

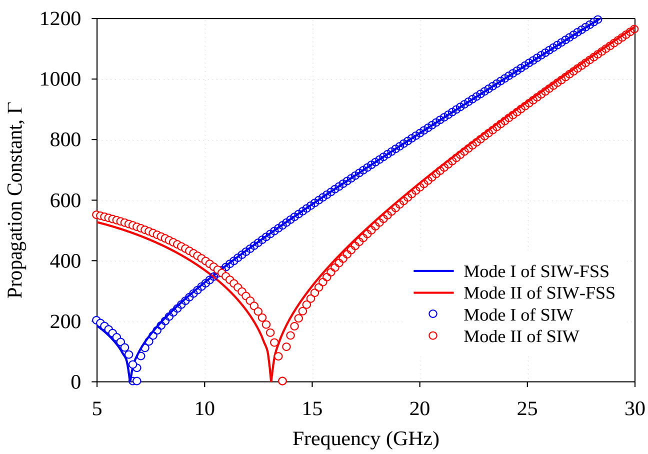


Figure 4 The complex propagation constant of RWG and SIW.

$$f_{c(TE_{10})} = \frac{c}{2\sqrt{\varepsilon_r} \cdot \left(W_{siw} - \frac{d^2}{0.95P} \right)} \qquad (4a)$$

$$f_{c(TE_{20})} = \frac{c}{\sqrt{\varepsilon_r} \cdot \left(W_{siw} - \frac{d^2}{1.1P} - \frac{d^3}{6.6P^2} \right)} \qquad (4b)$$

where c is light speed in air, ε_r is relative permittivity of the dielectric material.

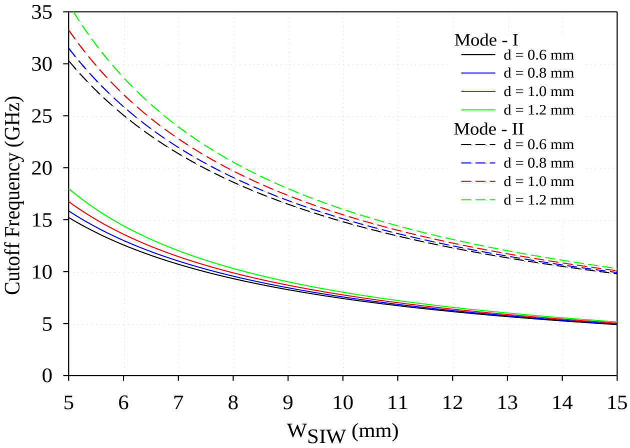
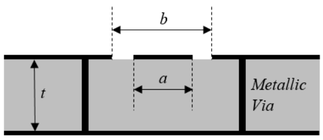


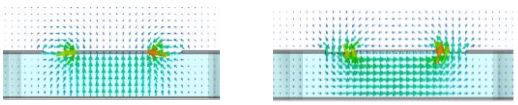
Figure 5 Cut off frequency of SIW as a function of SIW width (*Wsiw in* mm) for TE_{10} (mode 1) and TE_{20} (mode 2) mode (with p=1.55 mm).

D. Design of CPW feed

A grounded CPW (GCPW) has been used to excite the SIW-FSS structure. The GCPW using unique ground via structures are used here. Suppression of the higher order modes can increase GCPW bandwidth. The characteristic impedance (Z_0) offered by the feed structure can be computed by the Equation 5 [9]:



(a)



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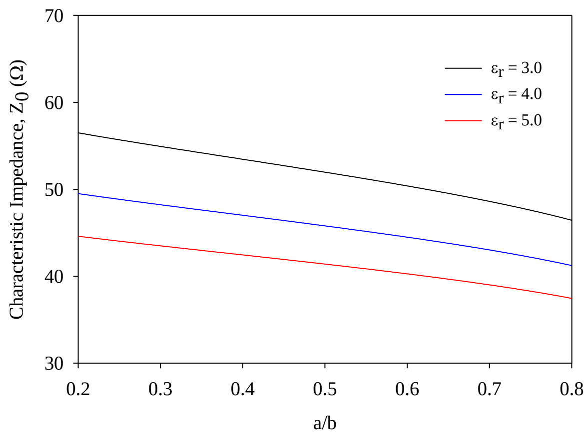


(c)

Figure 6 Design of GCPW: (a) Typical view of GCPW, (b) Mode of field excitation (left E-field and right H-field), (c) Characteristic impedance vs a/b.

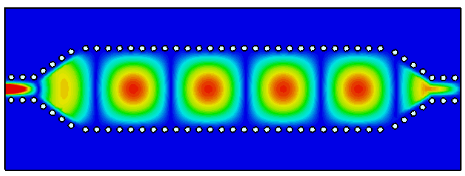
$$Z_0 = \frac{60\pi}{\sqrt{\varepsilon_{eff}}} \frac{1}{\frac{K(k)}{K(k')} + \frac{K(k_1)}{K(k_1')}} \qquad (5)$$

where, $k = a/b$ is $K(k)$ is the elliptical integral of the first kind and $K(k_1)$ elliptical integral of the second kind.

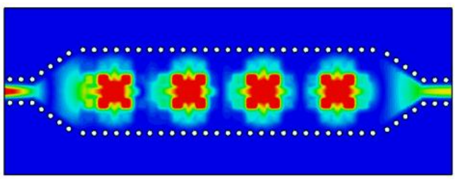
The metallic SIW vias are aligned on either side of GCPW to establish a connection with the ground. The structure is shown in Fig. 6(a). The width of CPW feed line is, $a = 1$ *mm* and $b = 1.6$ *mm*. The feed is analyzed on the same dielectric substrate with same thickness t. The formation of operating modes (*E*- and *H*-) are shown in Fig.6(b) and procedure to achieve 50Ω impedance as a function of design dimensions with a variable dielectric constant is illustrated in Fig. 6(c). The characteristic impedance When comparing microstrip, CPW and GCPW for the same circuit material and material thickness, GCPW circuitry has much less spurious generation and suffers much less EM radiation than microstrip circuitry and CPW for the same operating frequency. For higher-frequency circuits, GCPW can minimize dispersion compared to microstrip and CPW. However, GCPW is more sensitive to the copper plating thickness. The inherent advantages of GCPW over microstrip in terms of dispersion characteristics can be nullified unless a circuit with tight tolerance in copper plating thickness is specified.

III. Performance Analysis of SIW Structure Incorporated with FSS Element

The SIW dimensions have been obtained from the dispersion analysis. The designed parameters of SIW are $Wsiw = 11$ *mm* (from Fig. 5) length of SIW $L_{siw} = 50$ *mm* and $P = 1.55$ *mm* and $d = 0.8$ *mm* with substrate thickness $h = 0.508$ *mm*. Thus, the SIW structures with calculated dimensions have been designed and simulated using microwave studio (MWS) commercial software package. The *E*- field (absolute of the field component along *x*-, *y*- and *z*-directions) propagation of TE_{10} mode along its transverse direction, in analysed SIW structure incorporated with FSS element and their equivalent are presented in Fig. 7. The field is monitored at the centre plane (i.e., at $y = 0.25$ mm) of the dielectric substrate. The colour bar shows the *E*-field strength in structure. It is observed that mode behaviour does not alter in SIW topologies and *E*- field strength shown in equivalent SIW does not degrade after incorporation of FSS elements. Hence, the FSS element can be recommended as either top, bottom or both walls of a SIW. The frequency response of proposed SIW with GCPW has been analysed with incorporated JC FSS top wall and results are shown in Fig. 8.



(a)



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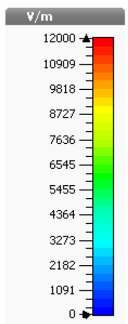

Figure 7 E-field (absolute of the field component along *x*-, *y*- and *z*-directions) distribution of TE_{10} mode at 10 GHz on the top surface of:
(a) Substrate Integrated Waveguide and (b) Jerusalem cross FSS-SIW.

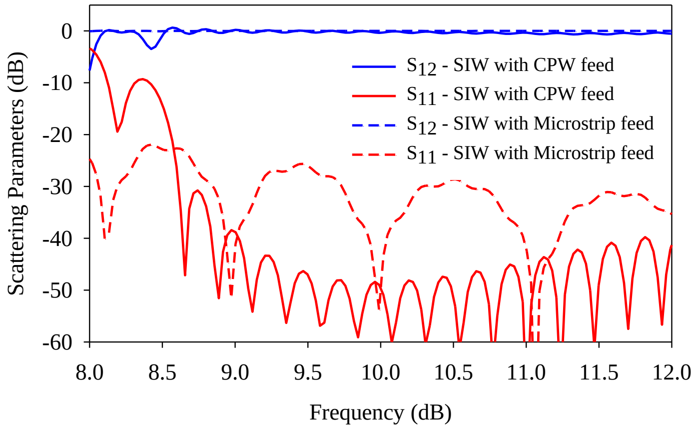

Figure 8 Frequency *vs.* S-parameters of SIW with FSS as reflecting top wall.

Fig.8 shows a comparison between the frequency response of SIW fed with microstrip and GCPW. A better isolation is observed in case of the proposed structure.

The presented analysis can be helpful for the design of bandpass filters and slotted waveguide antennas with proper selection of FSS element and its dimension.

IV. CONCLUSION

The accurate analytical modelling has been used to calculate complex propagation constant and cut off frequency of SIW structure. Periodic Jerusalem cross FSS element has been designed to operate in their stop bands and make them work as a perfect reflector at 10 GHz. The design procedure and characteristics of GCPW are presented in brief. Thus, the EM-field propagation is computed on the proposed structure and compared with conventional form. The performance analysis has been carried out on return loss and transmission loss of SIW incorporated with FSS as a PEC wall.

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