ANALYSIS OF MODE OF PROPAGATION IN SUBSTRATE INTEGRATED WAVEGUIDE USING FDTD

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***Abstract*— Substrate Integrated Waveguide is a hybrid of planar and non-planar structures. It is synthesized using the advantages of non-planar Rectangular waveguide for high power handling capacity, low losses and planar microstrip line for ease of fabrication , low profile and low weight. In this paper, an analysis of Substrate Integrated Waveguide is done by simulating a design in CST Microwave Studio, and mode of propagation present in the wave guiding structure is coded using MATLAB in one of the Numerical Computational Electromagnetics method namely (Finite Difference Time Domain) FDTD.**

***Index Terms*—Substrate Integrated Waveguide, Computational Electromagnetics, FDTD, Transverse Modes, Propagation Constant.**

I. INTRODUCTION

Classical waveguides are used for designing high performance systems. The high performance is attributed to their high power handling capability, high quality factor to name a few. But, unfortunately it is not possible to achieve a low cost mass production with this mature non-planar technology. Also, this scheme cannot give way to low weight and reduced volume designs. The planar counterpart on the other hand can result in low-profile, low weight and reduced volume deigns, but they fail to meet the power handling and quality factor requirements.

An integration of non-planar structures in planar technology was found to alleviate the drawbacks present in non-planar and planar techniques. This integration has given way to the so called hybrid structure, Substrate Integrated Waveguide (SIW). This is a promising candidate for microwave applications. This new concept has unified the hybrid and monolithic integrations of various planar and non-planar circuits that are made in single substrate and/or multilayer platforms. These hybrid devices involve both planar and non-planar structures realized and integrated on the same substrate using standard printed circuit board technology or other available planar processing techniques. They combine the advantages of planar circuits and metallic waveguides. This makes realization of non-planar structures in planar form feasible. This realization requires no transitions between elements fabricated with different technologies, and gives reduced losses and parasitics [1,2].

In this paper, an analysis of Substrate Integrated Waveguide is discussed with simulation tool Computer Simulation Tool (CST) and the mode of propagation is coded in MATLAB as well. The paper is organized as follows. At the outset, a description on basics of Substrate Integrated Waveguide is presented followed by the propagation modes existing in the waveguide. The design equations and simulation results are dealt with in the subsequent sections. Finally the paper is concluded .

BASICS ON SUBSTRATE INTEGRATED WAVEGUIDE

Substrate Integrated Waveguide is well known as post wall or laminated waveguide. It consists of electric walls on top and bottom of a dielectric substrate. These electric walls can be attributed to PEC (perfect electric conducting) or conducting sheets present on top and bottom of the dielectric. It consists of conducting cylinders on two sides of the waveguide which act as electric walls. These walls are formed by an array of PTHs (Plated Through Hole) present on either side of the dielectric. The array of PTHs together with the two conducting sheets on the substrate will do all functions of a non-planar waveguide in planar form. Thus an artificial waveguide can be constructed by embedding two linear arrays of metalized holes or posts on a single substrate used for planar circuitry [2, 3]. This synthesized waveguide is a good promising candidate between air-filled rectangular waveguide and planar circuit.

MODES OF EM PROPAGATION IN SIW

Transverse modes are present in SIW structures. They occur due to boundary conditions imposed on the electromagnetic wave by the waveguide. Here the boundaries are attributed to the conducting sheets on top and bottom of the substrate and the conducting posts on either sides of the substrate. When a mode is established in a guided wave structure, surface currents are also present in the same structure. A study of these surface currents will tell the mode of propagation. Only Transverse Electric (TE) modes exist in SIW. This can be explained as follows. The mode of propagation is determined by the conducting slots embedded in the substrate. If the slots are present such that they cut the currents, a large amount of radiation will be present. And if the slots are oriented along the direction of surface currents, a little radiation is present . In SIW, these slots do not cut the surface currents and so, the mode will be preserved within the structure. Thus only TE_{n0} modes exist in this synthesized waveguide [4].

DESIGN OF SUBSTRATE INTEGRATED WAVEGUIDE

The performance of SIW is decided by certain design parameters. A configuration of SIW synthesized using a linear array of metalized via holes is shown in Figure1. Earlier, the SIW structures were fabricated by mechanical process by drilling holes, inserting metal pins soldering the two metal sheets on top and bottom. If the metal posts are not soldered properly, the performance of SIW degrades. Hence, the metallic posts do have an important role to play. They not only shield the electromagnetic waves but also connect the surface currents in order to preserve the guided wave propagation. The set of equations required for designing SIW are discussed in the paragraph to follow [4].

The equation for effective width, w_{eff} is given by the following equation:

$$w_{eff} = w - \frac{d^2}{0.95 \times s} \quad (1)$$

The effective width of SIW will be between w and (w-d).The w_{eff} is dependent on w and ratio (d/s). The effect of ratio (d/w) is not included in the above equation. The actual empirical formula includes the effect of w and ratios (d/s) and (d/w) as given below.

$$w_{eff} = w - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{w} \quad (2)$$

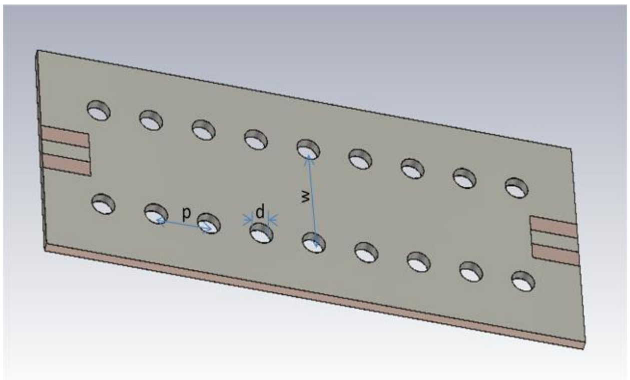

Fig. 1. Configuration of SIW structure synthesized using an array of metalized via holes

where w is given as ,

$$w = \frac{c}{2cos\theta\sqrt{\epsilon_r} f_l} \quad (3)$$

In the above equation, f_l is the lowest operating frequency of the structure and ε_r is the relative permittivity of the substrate. The other governing design equations are:

i) Select s/d < 2.5.
ii) Select d/w >1/5.
iii) Select the angle equal to larger than 30 and then calculate w using equation.(3)
iv) Calculate d and s accordingly.

From literature, it is understood that such a synthesized integrated waveguide cannot be considered as a normal homogenous waveguide and is an artificial periodic wave guiding structure. Also the simulations become insufficient and heavy, if a large number of metallic via posts are involved in the design. Hence in order to avoid this problem, the synthesized integrated waveguide is simply modeled as a standard dielectric-filled rectangular waveguide bounded by two parallel metallic walls [3].

RESULTS AND DISCUSSION

A synthesized integrated wave guiding structure was designed in electromagnetic software Computer Simulation Tool (CST) Microwave Studio which is based on Finite Integration Technique, a computational electromagnetics method [5]. Figure 2 shows a structure of SIW designed in CST. The values are designed following the design rules given in the previous section. The design parameters and their dimensions are as tabulated below.

Table1. Design parameters and their Dimensions

Design Parameter	Dimension in (mm)
Width of SIW	20.918
Diameter of VIA hole(PTH)	4.400
Spacing between the VIAs	9.960
Height of the substrate	1.600

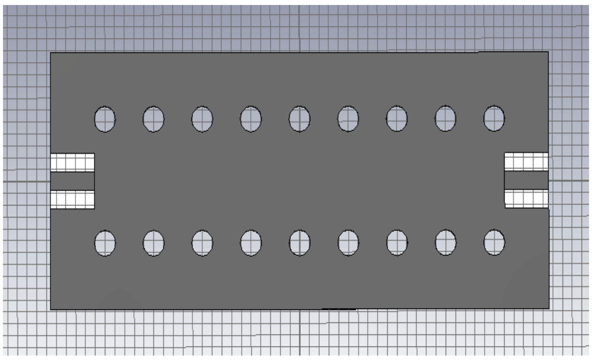

Fig. 2. Structure of SIW designed in CST

The designed structure was simulated from 1GHz to 8GHz.The various results obtained on simulating the above designed structure are as illustrated below. The performance of any wave guiding structure is of High-Pass nature, and hence the above synthesized structure also has similar response which can be understood from the variation of Transmission Coefficient as shown in Figure3. The cut-off frequency was also theoretically verified using the following equation

$$f = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \qquad (4)$$

The equation given above is one used to find the cut-off frequency of a rectangular waveguide where 'a' and 'b' are dimensions along the broader and narrower sides respectively. For TE_{10} mode m=1 and n=0. The value of cut-off frequency obtained from simulation is 3.95GHz. The value of cut-off frequency obtained after substituting for the width of SIW in the above equation was 3.83GHz which almost matches the simulation result for Transmission Coefficient. From the above result, we can infer that SIW preserves the characteristics of rectangular waveguide and also the dominant mode of propagation is TE_{10} as explained under the section for modes of EM propagation in SIW.

The S21 variation shows that SIW has a High-Pass response from the cut-off frequency of 3.95GHz. Hence it acts like a wave guiding structure. The simulated return loss characteristic is as shown in Figure4. From the variation of S11 with frequency, it can be inferred that after the cut-off frequency, the guiding structure has little losses and most of the energy is transmitted. The surface current distribution is as shown in Figure 5. The surface current distribution is well conforming to the one showed in [4] for TE_{10} mode. The surface currents are aligned along the post walls.

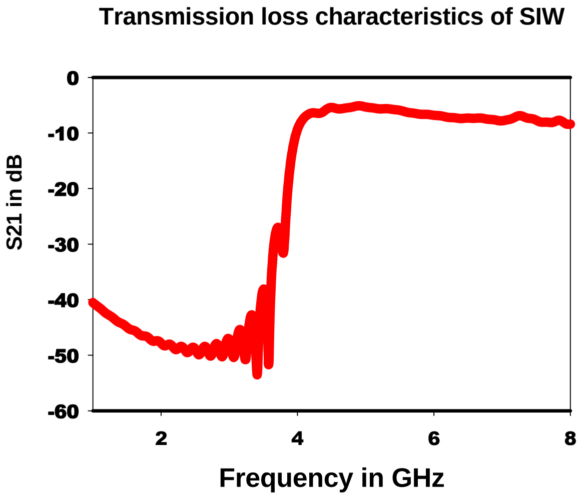

Fig. 3.Simulated Transmission Loss of designed SIW

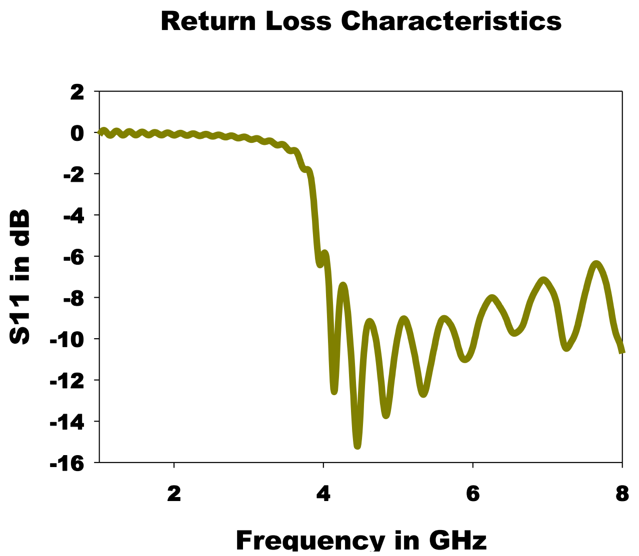

Fig. 4.Simulated Return Loss of designed SIW

This alignment shows that the mode is preserved in the structure as explained earlier . Hence the synthesized wave guiding structure allows TE_{10} mode to propagate along the structure. The E-field distribution for TE_{10} mode is as shown in Figure 6.

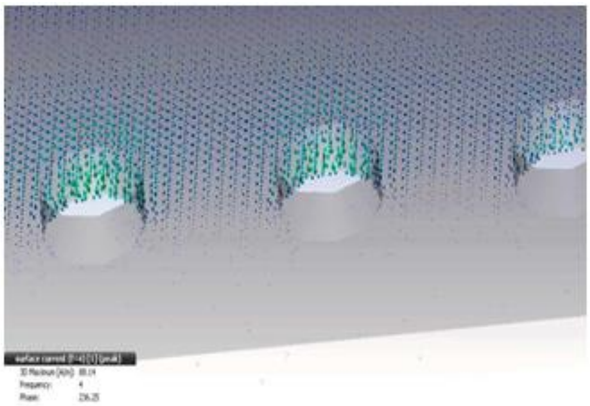

Fig. 5.Simulated Surface current distribution in SIW

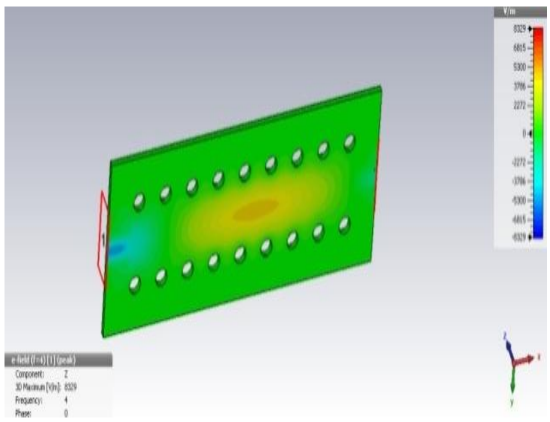

Fig. 6. Simulated E-field distribution in SIW

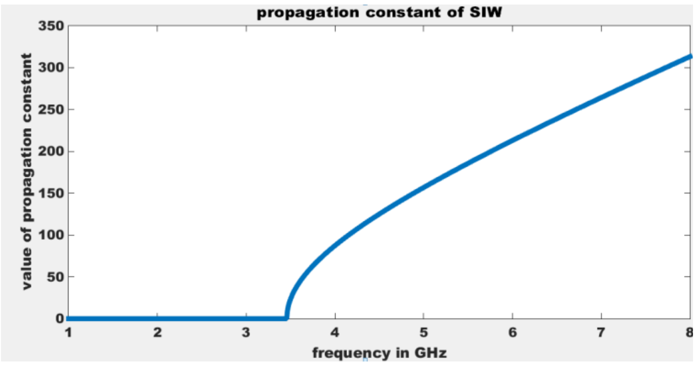

Fig. 7. Calculated Propagation constant for SIW in MATLAB

The field distribution in Figure 6 shows that the fields propagate between the two arrays of PTH holes, which act as electric walls. Thus the fields are confined between the two electric walls similar to a rectangular waveguide.

The propagation constant for the designed structure was coded in MATLAB and the obtained output is plotted in Figure 7. The equation used to find the propagation constant of SIW [6] is as given below ,

$$\beta = \frac{2\pi}{\lambda}\sqrt{1-\left(\frac{\lambda}{2a^{*}}\right)^{2}} \tag{5}$$

In the above equation, a^{*} is the width, 'w' of the SIW structure. λ is the range of wavelengths for which the designed structure was simulated, from 1GHz to 8GHz.From the variation of propagation constant with frequency, we can infer that, the designed structure allows the waves to propagate through it for frequencies above its cut-off frequency. The variation clearly shows that it acts like a wave guiding structure.

The mode of propagation in SIW, TE, was coded in MATLAB using the FDTD CEM (Computational Electro-Magntics) method. A numerical approximation of Maxwell's equations is known as CEM. CEM techniques form an invaluable part of current RF and microwave engineering practice. The Full wave CEM technique is potentially very accurate. They approximate Maxwell's equations without any initial physical approximations being made. FDTD is one of the full wave CEM techniques based on difference approach [5,7].

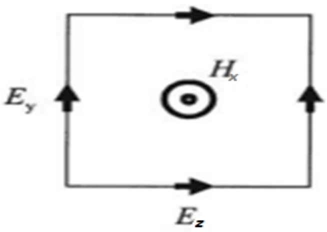

Fig. 8.Unit cell in FDTD for TE mode assuming propagation along x-axis.

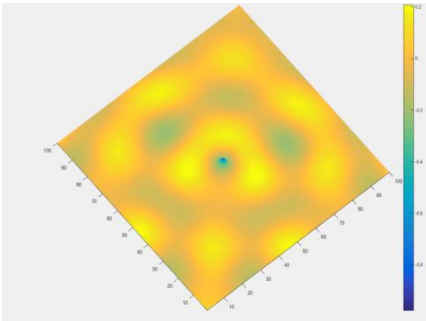

Fig. 9. Simulated FDTD for TE in MATLAB

It approximates differential operators in Maxwell curl equation on a grid staggered in time and space as proposed by Kane Yee. The electric fields are staggered at integral values of time and space steps, while the magnetic fields at half integral values of time and space steps. The Maxwell's equations in three dimensions were converted into two dimensions considering the underlying conditions like the direction of propagation, the fields present and absent along the axis of propagation etc. A unit cell of FDTD in two dimension for TE mode considering wave propagation along the x axis is as shown in Figure8. The fields were updated based on the Leap frog approach. According to this approach, E-field at the present instant depends on the value of E-field at the previous time instant and updated H-fields at the immediate previous instant. The set of equations used are as follows:

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon}\frac{\partial H_x}{\partial z} \tag{6}$$

$$\frac{\partial E_z}{\partial t} = -\frac{1}{\varepsilon}\frac{\partial H_x}{\partial x} \tag{7}$$

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left[\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y}\right] \tag{8}$$

The above partial differential equations were converted to differential forms . The time step and space step were chosen based on the Courant Stability Condition [7]. Excitation was given and absorbing boundary conditions were also considered at the edges of the computational space and the obtained output is as shown in Figure9.

CONCLUSION

A wave guiding structure based on a combination of planar and non-planar technology was designed. The nature of characteristics was confirmed through transmission loss curve and the mode of propagation in the synthesized structure was confirmed from the surface current distribution and E-field distribution. A Numerical Computational Electromagnetics method based on FDTD was used to code for TE mode, in MATLAB. The applications for this synthesized structure are myriad and researchers are still working to further explore the same.

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