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Frequency Sensitivity of a Substrate-Integrated WaveguideDevices by Finite Element Method

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ABSTRACT:Nowadays, many researches have been done to improve microwave devices operation. One of the newest and useful structures in microwave science is Substrate Integrated Waveguide (SIW) which has wide application in active and passive microwave circuits. This paper represented numerical calculation of frequency sensitivity of a SIW device using finite element.The finite element method (FEM) has been shown to be an efficient and flexible way for computing the equivalent circuit parameters of N-port planar devices (microstrip, stripline, rectangular waveguide, etc.).In this paper, the equivalent circuit parameters of the SIW line is calculated utilizing triangular FEM. Determining frequency sensitivity can be helpful in broadband calculation of circuit parameters. Since, in each simulation beside the circuit parameters their sensitivity relative to frequency is calculated. Therefore, the frequency sensitivity of the equivalent circuit parameters is alsodetermined**.**Good agreement is obtained with results of commercial software.

Keywords:Circuit parameters,Finite elements, Frequency sensitivity,Planar device, Substrate Integrated Waveguide (SIW).

I. INTRODUCTION

The Substrate-Integrated Waveguide(SIW), also called post-wall waveguide or laminated waveguide, is a promising candidate for millimetre-wave and terahertz application. This periodic waveguide, as illustrated in Fig. 1, is composed of two rows of conducting cylinders embedded in a dielectric substrate that connect two parallel metal plates. The first mention of this type of waveguide, to the best of the authors' knowledge, dates back to 1994 [1]. Since that time, a vast range of SIW components, such as filters, antennas, transitions, couplers, power dividers, and oscillators, have been proposed and studied. Such SIW structures can largely preserve the well-known advantages of conventional rectangular waveguides, namely, high-Q factor and high power capacity.

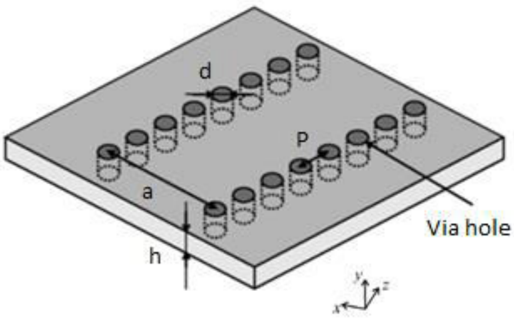

Fig.1Three-dimensional view of a SIW, with two rows of metallic cylinders.

In this paper we describe how Foster reaction theorem and finite element can be used to calculate sensitivity of a SIW to frequency using data of a single simulation only and at a little extra computational cost.

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A planar device can be defined as one in which electromagnetic fields do not vary significantly in one dimension [2-3] so that the simulation can be carried out in a plane. Substrate-integrated waveguide at dominant mode is an example of a perfect planar device.

Determining frequency sensitivity can be helpful in broadband calculation of circuit parameters.Since, in each simulation beside the circuit parameters their sensitivity relative to frequency is calculated. In resonant structures calculating frequency sensitivity due to change in structure parameter can be very useful for tuning bandwidth. Further, there have been some attempts at getting a computer to predict the best shape for a planar device, i.e., predicting the shape that minimizes return loss, gives a specified phase shift or division of power, and so on, where frequency sensitivity can be help to calculation the best shape for a planar device.

II. Analysis of SIW

The basic structure of the substrate integrated waveguide is the laminate with a waveguiding channel having an array of metallic vias. SIWs maintain the advantage of metallic waveguides like low losses and high power capacity, in addition combining them with the possibility of integration typical of microstrip structures.

A. Design Techniqueof SIW

Substrate integrated waveguide is made of a periodic via structure to realize bilateral edge walls. This periodic structure is much more complex for analysis than the conventional waveguide. Simulations of the integrated waveguide using a finite element method require abundant resources and the design of such a waveguiding structure is not straightforward. To improve the design efficiency, we transform the SIW to an equivalent rectangular waveguide.

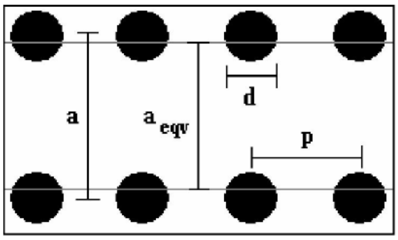

Fig.2SIW topology[5].

Theequivalent width of the SIW isprovided by following equation withvery good approximation [6].Where,P is sufficiently small.

$$a_{eff} = a_s - \frac{d^2}{0.95 \times P} \tag{1}$$

B. Components Design

Substrate integrated waveguidecomponents presented in this part are all designed on a Rogers RT/duroid 5880, with ε_r=2.2 and Thickness 0.787 mm. According to figure 2, the via diameter is d = 0.3mm and the pitch is p = 0.6mm. The distance of the bilateral via sidewalls is a = 6.686 mm. With the selected dimensions, we obtain an equivalent waveguide of dimension equal to a_{eqv}=6.528mm.

C. Frequency Sensitivity of a SIW

Because the final objective is to calculate the frequency sensitivity of SIW, we first begin by defining voltage and current at the SIW ports. We assume e_i and h_i are tangential electric and magnetic field at port $i$due just to the dominant mode wave incident on port i, when this wave carries unit real power into the junction region.

Generally, tangential electric and magnetic field on port $i$are:

$$E_t = V_i e_i \tag{2}$$

$$H_t = I_i h_i \tag{3}$$

This provides our definition of voltage $V_i$and current I_i at port i. It can be shown that the admittances and impedances we compute are normalized to wave impedance of the guide [3]. In view of thestructureshown in Fig.1and according

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tothe SIW at dominant mode is a perfectly planar device. In this paper, assumed field do not vary significantly in y dimension so the electric field can be represented as:

$$E = E(x,z)a_y \tag{4}$$

where,a_y is a unit vector in y dimension. Substituting (4) into the time-harmonic Maxwell'sequations, find that the equation governing E is:

$$\nabla \times \nabla \times E - k^2 E = 0 \tag{5}$$

It is simplifiedto 2-D scalar wave equation as below:

$$\begin{aligned} \nabla_t^2 E + k_0^{\,2}\varepsilon_r E = 0 \quad & on \quad \Omega \\ E = E_0 \quad & on \quad \partial\Omega_{D1} \\ E = 0 \quad & on \quad \partial\Omega_{D2} \\ \frac{\partial E}{\partial n} = 0 \quad & on \quad \partial\Omega_N \end{aligned} \tag{6}$$

where,Ω is area of the device, $\partial\Omega_{D1}$ is Dirichlet excitation interface, $\partial\Omega_{D2}$ is electric wall, $\partial\Omega_N$is magnetic wall and E_0 equals prescribed value of electric field due to unit power. It has been shown that solving the Eq. (6) is equivalent to solving the following variation problem [5].

$$\begin{cases} \partial F(E) = 0 \\ \text{E=0} \quad on \quad \partial D2 \\ E = E_0 \quad on \quad \partial D1 \end{cases} \tag{7}$$

Alternatively, it has been shown in [7] that the solution to the above equation is the stationary point of a functional:

$$F(E) = \frac{1}{2}\int_{\Omega} \{(\nabla_t E)^2 - k_0^{\,2}\varepsilon_r E^2\} d\Omega \tag{8}$$

This is the basis of the finite element analysis of SIW. By introducing functional, (8)is reduced to a matrix form:

$$F = \frac{1}{2}[E]^T([S] - k_0^{\,2}[T])[E] \tag{9}$$

where,[S] and [T] are well-known finite element global matrices [7-8]. After applying boundary condition it reduces to the form of [A].[E]=[b]. Solving the equation yields electric field on device. In addition,In [9] has been shown by the means of foster theory of reaction that susceptance sensitivity of a lossless device with respect to angular frequency can be calculated as:

$$\frac{\partial B}{\partial \omega} = \frac{4(W_m + W_e)}{VV^*} \tag{10}$$

where,W_e and W_m are average electric and magnetic energy respectively.If substitute the planar electric field from (1-3) it reduces to:

$$[S_{mn}] = \frac{-jb}{k_0\eta_0\omega_0}\int_{\Omega}\left\{\nabla_t E^{(m)}.\nabla_t E^{(n)} + k_0^{\,2}\varepsilon_r E^{(m)}E^{(n)}\right\} d\Omega \tag{11}$$

where m, n are port numbers, b is dimension of structure in y direction, η_0 is intrinsic impedance of free space, [S_{mn}] is normalized sensitivity matrix and $E^{(k)}$is electric field when there is normalized voltage on port k.Using triangular elements it reduces to the following equation:

$$[S_{mn}] = \frac{-jb}{k_0\eta_0\omega_0}[E]^T([S] + k_0^{\,2}[T])[E] \tag{12}$$

where*[S]* and *[T]* are well-known global matrices [7-8]. By means of (12) using the same data from simulation sensitivity of network parameters is calculated in addition to network parameters themselves.

III. RESULTS

A computer program has been written to implement above numerical method, single examples has been selected to verify the method in each case numerical results are compared with results of commercial software.

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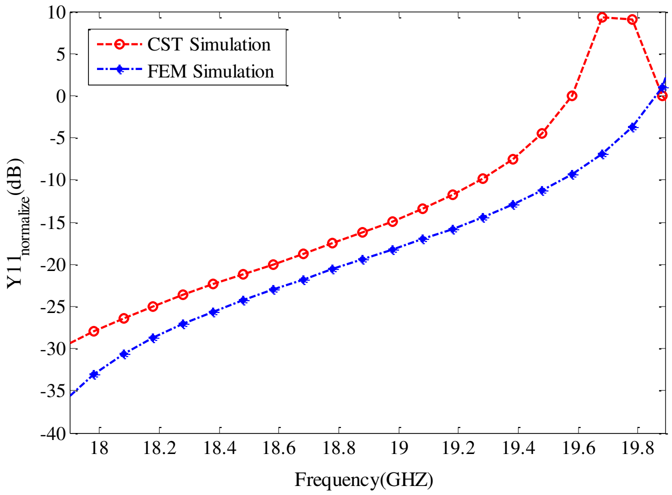

Fig.3: Y11parameter of SIW using our method and the same data obtained from software commercial CST

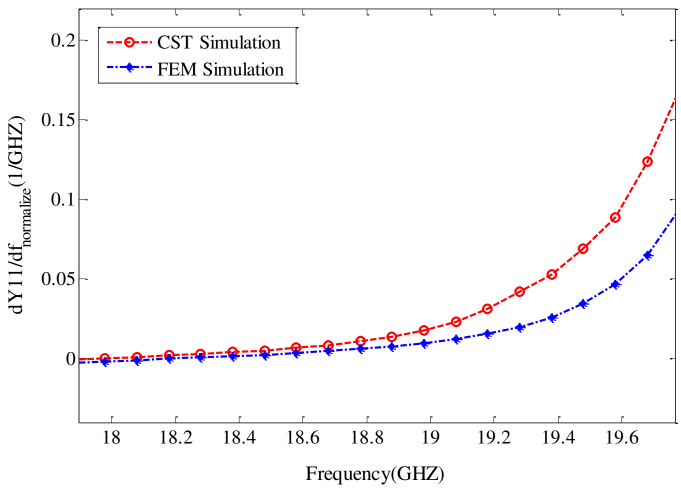

Fig.4: frequency sensitivity of SIW using our method and the same data obtained from software commercial CST

IV. CONCLUSION

It has been shown simulation data not only can be used for circuit parameters extraction, but also can be used in achieving frequency sensitivity. Frequency sensitivity can be lead to structure shape optimization. Determining frequency sensitivity can be helpful in broadband calculation of circuit parameters. Since, in each simulation beside the circuit parameters their sensitivity relative to frequency is calculated.In this paper, the equivalent circuit parameters of the SIW line has been calculated utilizing triangular FEM. Moreover, the frequency sensitivity of the equivalent circuit parameters has been also determined. Good agreement has been obtained with results of commercial software.

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