SIW ferrite circulator design and modeling using the WCIP method

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Abstract. In this paper, a study of circuits SIW (Substrate Integrated Waveguide) based on the integration of ferrite cylinders in the substrate is used to design ferrite circulator. To describe the behavior of electromagnetic fields into the ferrite cylinder, Maxwell's equations should be considered to calculate the EM fields. Firstly, a design of structure SIW containing ferrite via-holes is presented. Then, the Iterative Method (WCIP) based on the Wave Concept is developed where both the spatial and spectral relationships are determinate; the reflection coefficient connecting the waves in the spectral domain and the spatial diffraction operator are deduced.

Keywords: Ferrite circulator, Substrate Integrated Waveguide, WCIP method.

1 Introduction

For several years, a study of microwave integrated circuits has been the subject of a lot of work done. This research has led to the integration of waveguides into the substrate SIW (Substrate Integrated Waveguide) [1, 2], what is constituting new types of transmission line.

Particular attention will be paid to the waveguide circulators [3] which are the most suitable for this type of circuit. These components use thin magnetic materials that give them non-reciprocity which are ferromagnetic materials: ferrites remain materials of choice for these applications [4].

These circuits may be analyzed by different methods Method of Moments (MoM) [5] or Finite element method (FEM) [6], Greens function [7]... Recently, the Iterative Method (WCIP) based on the Wave Concept [8] is considerate to study the substrate integrated structures. This method has been successfully adapted to SIW circuits [9]. It has shown its efficiency and speed in the treatment of this type of structures.

In this work, a design analysis of electromagnetic circulator-in a SIW structure is done which allows the integration of non-reciprocal devices in the substrate based on ferrite cylinders using the iterative method based on the concept of waves (WCIP).

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2 Design of SIW Structure

In this paper, a structure allowing the integration of a complete system on the substrate using ferrite vias playing the roles of circulators seemed to be a reliable solution. Thus, the circular waveguide can be integrated into the substrate via rows of metalized holes delimited by periodic walls. This set of via holes delimits a guide in which the modes will appear.

The structure studied is composed of elementary cells (ferrite cell, source cell, metal cell,...) distributed over a periodic frame as shown in Fig. 1.

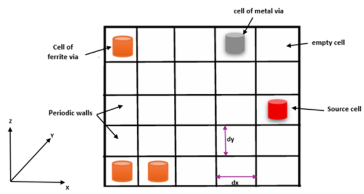

Figure 1. General configuration of SIW structure

The problem is solved by considering a cell called "elementary cell" which is represented by Fig. 2.

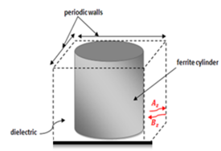

Figure 2. Elementary cell

An elementary cell isolated from the overall structure is considerate. The fields are directed in the Z direction and the structure can be reduced to a 2-D problem, where a cylindrical coordinate system will be used. Thus, for each elementary cell, the electric field and the current density are denoted successively $\mathbf{E}_z$ and $\mathbf{J}_z$.

3 WCIP Formulation

The Iterative Method (WCIP) based on the Wave Concept has been the subject of many researches and publications [10, 11]. Recently, this method is modified to study SIW structures and proves a great adaptation with this type of structures [9].

The WCIP method introduces a concept of incident waves $\mathbf{A}$ and the reflected waves $\mathbf{B}$ [12–14] defined by the following expressions:

$$\mathbf{A} = \frac{1}{2\sqrt{Z_0}}(\mathbf{E}_z + Z_0\mathbf{J}_z) \tag{1}$$

$$\mathbf{B} = \frac{1}{2\sqrt{Z_0}}(\mathbf{E}_z - Z_0\mathbf{J}_z) \tag{2}$$

With Z_0 represents an arbitrary impedance. According to equation (1), the expressions of the tangential component of the electric field $\mathbf{E}_z$ and the current density $\mathbf{J}_z$ can be obtained:

$$\mathbf{E}_z = \sqrt{Z_0}(\mathbf{A} + \mathbf{B}) \tag{3}$$

$$\mathbf{J}_z = \frac{1}{\sqrt{Z_0}}(\mathbf{A} - \mathbf{B}) \tag{4}$$

Firstly, the EM fields existing in the magnetized ferrite cylinder will be governed by Maxwell's equations. Applying the boundary conditions, the spatial and spectral relations will be determinate. Then, both the reflection coefficient connecting the waves in the spectral domain and the spatial diffraction operator will be deduced.

3.1 Relations in the spatial domain

The boundary and continuity conditions for the EM fields are expressed in terms of wave by using a diffraction operator $\hat{S}$. This operator connects the waves in the spatial domain by the relation:

$$\mathbf{A} = \hat{S}\mathbf{B} + \mathbf{A}_0 \tag{5}$$

where $\mathbf{A}_0$ is a source term to specify which via hole is excited initially. And the spatial operator is written as:

$$\hat{S} = -\hat{H}_M + \Gamma_S \hat{H}_F + \hat{H}_S \tag{6}$$

With $\hat{H}_F$, $\hat{H}_M$ and $\hat{H}_s$ denote the Heaviside functions, with M, F and S represent the via metallic, ferrite or source. $\hat{H}_i = 1$ on the area of i and equal to zero otherwise, with i represents metallic via, source via or ferrite via.

Γ_s represents the reflection spatial operator is given by:

$$\Gamma_S = \frac{Z_{Si} + Z_0}{Z_{Si} - Z_0} \tag{7}$$

With Z_{Si} of spatial surface impedance for the ferrite via corresponding to significant propagative mode i, it is defined for the three first modes $(-1, 0, 1)$ by the following equation:

$$Z_{s\to 1} = \frac{E_z^{-1}}{J_z^{-1}} = \frac{J_{-1}(k_{eff}r)}{-\beta\{\mu_{eff}J_{-1}(k_{eff}r) - \frac{\alpha}{r}J_{-1}(k_{eff}r)\}} \tag{8}$$

$$Z_{s0} = \frac{E_z^0}{J_z^0} = \frac{J_0(k_{eff}r)}{-\beta\{\mu_{eff}J_0(k_{eff}r)\}} \tag{9}$$

$$Z_{si} = \frac{E_c'}{J_z'} = \frac{J_1(k_{eff}r)}{-\beta\{\mu_{eff}J_1(k_{eff}r) + \frac{\alpha}{r}J_1(k_{eff}r)\}} \tag{10}$$

With:

$$\begin{cases} k_{eff}^2 = \omega^2\mu_{eff}\varepsilon_0\mu_0 \\ \mu_{eff} = \frac{\mu^2 - k^2}{\mu} \end{cases} \tag{11}$$

J_p is the Bessel function of order 1 and a_p are the modal coefficients. μ_0, ε_0 et ε_r are respectively the permeability, the permittivity and the relative permittivity of the material supposed isotropic.

3.2 Relations in the spectral domain

To describe the response of the external environment around the ferrite via, an operator called is used. Indeed, binds the incident waves **A** and the reflective waves **B** in the modal domain by the following relation:

$$\mathbf{B} = \hat{\Gamma}\mathbf{A} \tag{12}$$

This operator is expressed in the following form:

$$\hat{\Gamma} = \sum_{pq} |F_{pq}\rangle \overline{\Gamma}_{pq} \langle F_{pq}| \tag{13}$$

$$\overline{\Gamma}_{pq} = (\overline{Z}_{pq} - Z_0 I)(\overline{Z}_{pq} + Z_0 I)^{-1} \tag{14}$$

where F_{pq} is the basic function of the modes of the box containing the circuit (the basic function of the overall structure) and $\overline{Z}_{pq}$ is a matrix of the modal impedance characterizing the via hole coupling in the SIW circuit.

3.3 Iterative process

The WCIP method based on waves concept consists in establishing a recurrence relation between the incident waves **A** and reflected waves **B** in two different domains (spectral and spatial) which constitute the iterative process (Fig. 3). The iterative process is exciting by the feeding source $\mathbf{A}_0$. The transition between the two domains is through a Fast Fourier Transform (FFT) and its inverse transformation (FFT^{-1}) [15].

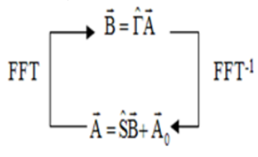

Figure 3. Iterative process

4 Application

In this work, it is proposed to study SIW circuits that allow the integration of non-reciprocal devices in the substrate based on ferrite cylinders. The proposed structure allows the integration of rows of ferrite conductive cylinders that form a circulator with 3 symmetrical ports, delimited by electrical walls based on metal cells.

The studied structure is composed of elementary cells (source cell, metal cell, ferrite cell, ...) distributed over a periodic frame as shown in Fig. 4 below.

Based on the theoretical formulation, the WCIP method will be implemented to calculate the circulation of EM fields in the ferrite vias network.

The variation of the reflection spatial versus the frequency is shown in Fig. 5 for an internal field $H_i = 8 \times 10^5$ A/m, a saturation of magnetization $M_s = 16 \times 10^5$ A/m, $\mu = 0.01$ and for a value of radius $R = 1.5$ mm.

As shown in figure 5, the resonance frequency is 16.48 GHz. It is shown that the device presents a resonance frequency at $f = 16.38$ GHz.

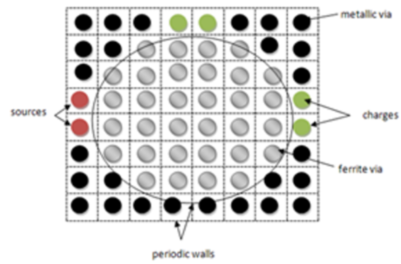

Figure 4. Design of a ferrite circulator

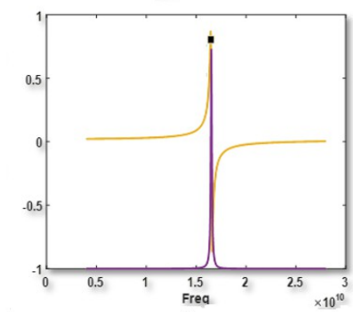

Figure 5. Variation of the spatial reflection component versus the frequency.

For the same proposed design in Fig. 4, the electric field $|E_z| = |\mathbf{E}_z|$ of the guide is represented at 16.38 GHz for the same physical parameters of the Polder tensor. The distribution of the electric field inside the device is plotted in Fig. 6 after the convergence of the iterative process, in considering 64×64 ferrite via holes.

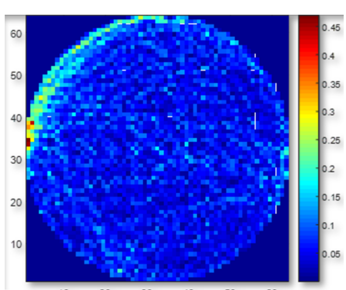

Figure 6. Distribution of the electric field Ez inside the ferrite circulator.

A notable observation reveals that the electric field tends to propagate near the surface of the ferrite material. Furthermore, this propagation follows a specific pattern: the electric field circulates in one direction, flowing from the excitation ports towards the third port. However, it is worth noting that the electric field is effectively blocked in the opposite direction, preventing its movement.

Fig. 7 illustrates the changes in the S_{ij} parameters of the studied structure while keeping the previous dimensions and physical parameters.

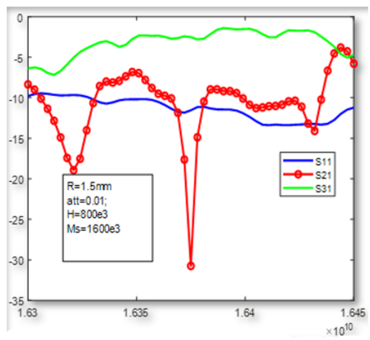

Figure 7. Variation of s-parameters (insertion loss S31, isolation S21, return loss S11).

The analysis of Fig. 7 shows that the circulator operates at a frequency of $f = 16.38$ GHz. An isolation factor of 15 dB, a return loss of 32 dB, and an insertion loss of 1 dB were observed.

5 Conclusion

The purpose of this study was to design and model an electromagnetic circulator using the substrate integrated wave (SIW) circuit and the iterative process method based on the concept of waves. A ferrite circulator is designed by incorporating a ferrite via hole into a substrate integrated waveguide (SIW) structure. The WCIP is subsequently developed to calculate the electric field inside the circulator and the S-parameters.

The distribution of the electric field inside the device exhibits an anisotropic effect caused by the presence of ferrite. This observation is further reinforced by the S parameter.

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