



Anisotropic Metamaterials Filled Rectangular Metallic Waveguides Propagation Study and Analysis

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

In this paper, we propose a novel generalized S-matrix characterization approach. The goal is to keep track of all observed discontinuities as efficiently as possible. In terms of reflection value, the proposed control strategy is based on transmission coefficients and one-axis rectangular guides. We successfully manipulate metal rectangular waveguide filters with both geometrical and physical discontinuity. Lossless discontinuity is depicted as a periodic structure that contains Metamaterials. The modal development of transverse fields provides the basis for the generalized S-matrix approach. The approach works by breaking down electromagnetic fields for each of the guides that make up the discontinuity on an orthonormal basis. When the Galerkin method is used, the matrix of diffraction of the junction is obtained directly.

Keywords: Electromagnetic fields; orthonormal basis; Galerkin method; matrix.

1. INTRODUCTION

We present a first step in the very extensive formulations of the modal coupling method MRM, which uses the modal decomposition of fields to

calculate the dispersion and hence the matrix and characterization of a waveguide discontinuity [1]. Following that, a few rectangular guide applications are presented. The MRM associated (MSG) generalized S-matrix technique is used to

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model filters in rectangular metal guides to physical junctions due to media discontinuities. In the next stage, To study an isotropic medium [2] filled rectangular filter including complicated geometric shape iris, we provide a hybridization of the finite element technique (FEM) with the multimodal variation on MVM. Under HFSS simulation and measurement, we compare our methods. It is possible to make a good comparison. Furthermore, the developed approach is substantially faster than HFSS. Case Study on Complex Discontinuities Filters When employing modal methods, the size of the dispersion matrix is determined by the total number of modes at the circuit's entrance and exit.

2. COMPLEX DISCONTINUITIES FILTERS STUDY CASE

The size of the scattering matrix [3] in our multimodal variational formulation [4] is only determined by the number of available modes, which is independent of the total number of modes and contributes to the electromagnetic field near the series form of discontinuities terms, without affecting the final dispersal S matrix. In comparison to other modal methods such as the MRM and the MSG, the reduction in the size of the scattering matrix reduces memory storage and convergence time [5]. The matrix S of each discontinuity is calculated in advance by studying discontinuities in cascades. The entire circuit's response is obtained by connecting all of the S matrices with their corresponding waveguides. As a result, in the study of intermediate discontinuities, the number of possible modes must be carefully chosen. When the discontinuities are narrower or the fundamental mode is formed, convergence is necessary to assure the accuracy of the overall S matrix. A multimodal modified variational formulation (FMVM) was presented to have any convergence situation, with the goal of studying a simple cascade discontinuity [6]. Rather than establishing variational forms for each discontinuity as in, a global variational form based on a vector of electrical fields that includes all existing discontinuities is used. As a result, the size of the overall dispersion matrix is only determined by the number of modes accessible at the structure's entrance and exit. When dealing with a waveguide made up of arbitrary cut iris, however, the modal basis is analytic, and numerical values and vectors will significantly boost CPU TEMPS. The application of spatial discretization techniques, GEF (finite elements

approach), and the production of correct findings. By combining the MVM and the GEF, we shall present a novel hybrid schema. The electric field at the level of the complex discontinuity will be developed in the basis of finite elements wherever it is created in a modal basis. The complicated discontinuity's surface will be partitioned into a number of rectangular or triangular components. The tangential electric field within each element will be approximated by a combination of twin functions defined [7] by the element's edges. It does, however, employ additional analytical calculations to reduce computing time and memory requirements. This technology enables the performance of numerous passive microwave components like as filters, antennas, and shifters to be successful. Variation Analysis of the Multimodal Classic Consider the intersection of two uni-axiaux guides (Fig. 1), where the guide walls are almost perfect conductive. It uses the following connection to define current density at the interface between guides: (1) is the unit vector normal to the interface of the guides and the tangential magnetic field at the interface in the guide $i(i=I, II)$. The following equations relate the current density and the tangential electric field at the interface: (2)Where (3) Is the acknowledgment of the discontinuity, as follows: The m in the guide I mode projector is (4). - Is the decreased admission reduced to the m mode plan guide? i .-is the m mode's current density. -in the guide I is a constant of normation m mode fields, defined by: The Kronecker sign is (5): There are two parts to the Two Guides interface: -isolating the part of the circuit where the current density is zero. -A metal portion with no tangential electric field. As a result, we have: The operator (6) is a self-adjoin operator. When metal and dielectric losses aren't considered, the relationship ship A variational version is (6). (7) When dealing with a discontinuity, the goal is to minimize form variation. If the tangential electric field is broken down using testing functions. If the tangential electric field is broken down using proper test functions, we get: (8)By inserting (7)'s phrase inside (6), we get: (9)The form is stationary [8], and ero is its derivate: (10)Where and are the number of accessible modes at the entry and exit, respectively. We extended the hybrid approach proposed in to analyze complex one 2D discontinuities in cascades to quickly and accurately construct isotropic [8] rectangular filters with complex iris [9]. We shall present an original hybrid schema by combining the MVM with the GEF in the following sections. The electric field at the level of the complex

discontinuity will be developed in the basis of finite elements wherever it is created in a modal basis. The complicated discontinuity's surface will be partitioned into a number of rectangular or triangular components. The tangential electric field within each element will be approximated by a combination of twin functions defined [10] by the element's edges. By blending the functions of tweens, the data base functions of trials in the full surface of discontinuity [7] will be determined. We discuss the advantages of the hybrid method [11] offered in comparison to numerous CAD products.

3.MULTIMODAL VARIATIONAL METHOD IMPLEMENTATION

Implementation of a Multimodal Variational Method MVM, a method developed in the laboratory LAPLACE, INP ENSEEIHT, is a variant of the modal connection approach MRM (Matching mode) that has proven to be a very successful tool for modeling one discontinuity [12]. However, it will only evaluate a limited number of modes to reflect any modal basis in practice (spectral truncation).

3.1 Variation Multimodal Classic Analysis

Consider the junction between two uniaxial guides, the walls of the guides is similar to perfectly conductive. It defines the current density at the level of the interface between guides as the following relationship:

$$\vec{J} = \left(\vec{H}_t^{(1)} - \vec{H}_t^{(2)} \right) \times \vec{n} \quad (1)$$

$\vec{H}_t^{(i)}$ is the tangential magnetic field at the interface in the guide i (i=I, II) and \vec{n} the unit vector normal to the interface of the guides here \vec{z} . The current density and the tangential electric field to the interface are related by:

$$J(z_0) = \hat{Y} E_t(z_0) \quad (2)$$

Where

$$\hat{Y} = \sum_{n=1}^{+\infty} y_n^{(1)}(z_0) \hat{Y}_n^{(1)} + \sum_{m=1}^{+\infty} y_m^{(2)}(z_0) \hat{Y}_m^{(2)} \quad (3)$$

\hat{Y} Is the admittance of the discontinuity, with:

$$\hat{Y}_m^{(i)} = \left| j_m^{(i)} \right\rangle \frac{1}{N_m^{(i)}} \left\langle j_m^{(i)} \right| \quad (4)$$

- $\hat{Y}_m^{(i)}$ is the m in the guide i mode projector.

- $y_m^{(i)}(z_0)$ is the reduced admittance reduced to m mode plan guide i.

- $J_m^{(i)}$ is the current density of the m mode.

- $N_m^{(i)}$ is a constant of normation m mode fields in the guide i, defined by:

$$N_m^{(i)} \delta_{mn} = \left\langle e_m^{(i)} \left| j_n^{(i)} \right\rangle \quad (5)$$

δ_{mn} is the Kronecker symbol:

$$\delta_{mn} = \begin{cases} 1 & si \ m = n \\ 0 & si \ m \neq n \end{cases}$$

The two guides interface contains two parts:

-Insulating part where the current

$J(z_0)$ density is zero.

- Metal part where the tangential electric field $E_t(z_0)$ is null.

Therefore we have:

$$\hat{Y} E_t(z_0) = 0 \quad (6)$$

\hat{Y} is a self-adjoin operator.

When the metal and dielectric losses are not take n into account, the relationship (6) is a variational form.

$$f(E_t) = \left\langle E_t \left| \hat{Y} E_t \right\rangle \quad (7)$$

For a discontinuity, the search for the solution is t o minimize form variation.

If it breaks down the tangential electric field on a basis of testing functions.

If it breaks down the tangential electric field on the basis of appropriate test functions, we have:

$$E_t = \sum_{q=1}^{\infty} C_q f_q(x, y) \tag{8}$$

By introducing the expression of (7) in (6), we have:

$$f(E_t) = \left\langle \sum_{q=1}^{\infty} C_q f_q(x, y) \left| \hat{Y} \sum_{p=1}^{\infty} C_p f_p(x, y) \right. \right\rangle \tag{9}$$

The form is stationary [8], its derivate C_p is zero:

$$\begin{aligned} & \sum_{q=1}^{+\infty} \left(\sum_{n=1}^{m_1} y_n^{(1)}(z_0) \langle f_p(x, y) | \hat{Y}_n^{(1)} f_q(x, y) \rangle + \sum_{m=1}^{m_2} y_m^{(2)}(z_0) \langle f_p(x, y) | \hat{Y}_m^{(2)} f_q(x, y) \rangle \right. \\ & \left. - \sum_{n=m_1+1}^{+\infty} \langle f_p(x, y) | \hat{Y}_n^{(1)} f_q(x, y) \rangle - \sum_{m=m_2+1}^{+\infty} \langle f_p(x, y) | \hat{Y}_m^{(2)} f_q(x, y) \rangle \right) C_q = 0 \end{aligned} \tag{10}$$

With $p = 1, 2, \dots, \infty$,

Where m_1 and m_2 are the number of accessible modes respectively at the entrance and exit. These modes are diffracted propagatifs and evanescent modes involved in coupling of two successive discontinuities.

It defines the matrices Q , $N^{(i)}$, $Y^{(i)}$ and $U^{(i)}$ and as follows:

$$Q_{pq} = -j \left[\sum_{n=m_1+1}^{+\infty} \langle f_p(x, y) | \hat{Y}_n^{(1)} f_q(x, y) \rangle + \sum_{m=m_2+1}^{+\infty} \langle f_p(x, y) | \hat{Y}_m^{(2)} f_q(x, y) \rangle \right] \tag{11}$$

$$N^{(i)} = \begin{bmatrix} N_1^{(i)} & 0 & 0 & \dots & 0 \\ 0 & N_2^{(i)} & 0 & \dots & 0 \\ 0 & 0 & \cdot & \dots & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & \dots & N_{m_1 \text{ ou } m_2}^{(i)} \end{bmatrix} \tag{12}$$

$$Y^{(i)} = \begin{bmatrix} y_1^{(i)}(z_0) & 0 & 0 & \dots & 0 \\ 0 & y_2^{(i)}(z_0) & 0 & \dots & 0 \\ 0 & 0 & \cdot & \dots & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & \dots & y_{m_1 \text{ ou } m_2}^{(i)}(z_0) \end{bmatrix} \tag{13}$$

$$U_{p,n}^{(1)} = \langle f_p(x, y), j_n^{(1)} \rangle \quad n = 1, 2, \dots, m_1 \quad (14)$$

$$U_{p,n}^{(2)} = \langle f_p(x, y), j_n^{(2)} \rangle \quad n = 1, 2, \dots, m_2 \quad (15)$$

A calculation allows determining the impedance of the discontinuity that is defined matrix as follows:

$$Z = -jN^{-1}N^{+1/2}\Gamma N^{-1/2} \quad (16)$$

$$\Gamma = \begin{bmatrix} U^{(1)*T}Q^{-1}U^{(1)} & U^{(1)*T}Q^{-1}U^{(2)} \\ U^{(2)*T}Q^{-1}U^{(1)} & U^{(2)*T}Q^{-1}U^{(2)} \end{bmatrix} \quad (17)$$

The symbol ($*T$) represents the conjugate transpose.

The analysis of a simple discontinuity by the MVM boils down to the determination of the scalar product between the basis of testing functions and modes of the two guides,

i.e. the determination of the matrix Γ .

From the impedance matrix Z , the matrix S of discontinuity will have the following form:

$$S = (Z + I)^{-1}(Z - I) \quad (18)$$

The number of modes used in the formulation is infinite. However, we consider a finite number of modes to represent any modal basis (spectral truncation). Should sort modes of the two sets by increasing cuts frequencies guidelines [13] and take the modes that appear first for best performance.

4. NMVM DISCONTINUATY ANALYSE METHOD

It is considered a structure with N one discontinuities cascading as shown in Fig.1.

\vec{H}_t^i (Respectively \vec{H}_t^{i+1}) in the transverse magnetic field guide i (respectively $i + 1$)

\vec{n} is the unit vector in the z direction.

For a structure with several one discontinuities in cascade, the dispersion of all matrixes

Discontinuaty Analyse Method NMVM As seen in Fig. 1, it is a structure with N one discontinuities cascading. $\vec{1}$ (respectively $\vec{1} + 1$) is the unit vector in the z direction in the transverse magnetic field guidance. The dispersion of all matrices for a structure with numerous one discontinuities in cascade is derived by chaining individual discontinuities dispersion matrix. Modal approaches like modal connection (MRM), matrix S-widespread (MSG), and MVM are frequently used to determine these S matrices. The MV Mover has an advantage over other approaches in that the dimensions of the S matrix are determined by the number of available modes, not the total number of modes. This saves both store space and processing time. However, a study of convergence based on the number of possible modes in the constituent guides is required for the best results. A new formulation of the MVM (NMVM) has been developed to bypass this study of convergence and save calculation time. All higher order modes in the intermediate guides [14] are taken into consideration in this revised formulation, which increases the accuracy of the analysis. A calculation can be used to determine the impedance of a discontinuity described as follows: (16) (17) The conjugate transpose is represented by symbol. The MVM's analysis of a simple discontinuity boils down to determining the scalar product of the two guides' foundation of testing functions and modes, i.e. determining the matrix. The discontinuity matrix will have the following form based on the impedance matrix: (18) The number of modes employed in the formulatio is theoretically unlimited.

4.1 NMVM and Finite Element Hybridization Analysis

The discontinuity matrix will have the following form based on the impedance matrix: (18) The number of modes employed in the formulatio is theoretically unlimited. Hybridization Analysis Using NMVM and Finite Element Methods We consider a set of several 2D complex one discontinuities between a rectangular wave guide [15] filled with isotropic [16] medium, with \vec{e} representing the discontinuity's opening. and represent the medium's relative dielectric constant [17] and relative permeability [18].

$$f(E_t) = \left\langle \begin{pmatrix} E_{t1} & E_{t2} & \dots & E_{tM} \end{pmatrix} \hat{Y} \begin{pmatrix} E_{t1} \\ E_{t2} \\ \vdots \\ E_{tM} \end{pmatrix} \right\rangle \quad (19)$$

$\langle \cdot | \cdot \rangle$ denotes a scalar product, is the number of one discontinuities and \hat{Y} being the matrix operator self-adjoint admittance of a structure complete. When we consider simple open S_i of (restrictions rectangle, circle, ellipse, etc...)

the tangential electric field E_{ti} of the discontinuity can be decomposed on the modal basis of Eigen functions which satisfies a boundary conditions. When we consider the complex multiple opening.

The determination of modal base of eigen function is more obvious. To determine this deficiency, we will replace the spectral discretization via space discretization. At the level of the complex discontinuity, the tangential electric field will be decomposed in the base of the vector finite elements. Our goal is to write the electric field in a manner similar to equation (7) as follows:

$$E_t = \sum_{q=1}^{\infty} C_q f_q(x, y) \quad (20)$$

The first step is to mesh the surface of discontinuity S only elements. In a electric field can be triangular element, written as follows:

$$E_t^e(x, y) = \sum_{m=1}^3 E_m^e N_m^e(x, y) \quad x, y \in e \quad (21)$$

E_m^e denotes the tangential electric field along the same edge. We choose the first-order interpolation function. Condition between two adjacent elements, the tangential electric field

in the opening of S_i can be expressed as follows :

$$E_{ti}(x, y) = \sum_{pi=1}^{Ni} B_{pi} g_{pi}(x, y) \quad (22)$$

N_i denotes the number of edges in the opening S_i .

B_{pi} denoted the unknown tangential-electric field along the edge EEP.

To determine the $g_{pi}(x, y)$ (are new interpolation functions), we have two cases: the first is if the p^{eme} edge is in the border of the opening S_i ,

B_{pi} the coefficients play the same role as C_q in the relationship (20). As a result, they will be disposed of in the MVM formulation

$$g_{pi}(x, y) = N_m^e(x, y) \quad x, y \in e \quad (23)$$

And the second case is if the p^{eme} edge is inside the opening S_i , it can belong only to two adjacent (e) elements and (e'). As a result, the edge will

define two functions $N_m^e(x, y)$ and $N_{m'}^{e'}(x, y)$ interpolation that have opposite directions. Thus:

$$g_{pi}(x, y) = N_m^e(x, y) - N_{m'}^{e'}(x, y) \quad x, y \in \{e, e'\} \quad (24)$$

By combining equations 19 and 21 we obtain the following function:

$$f(E_t) = \left\langle \begin{pmatrix} \sum_{p1=1}^{N1} B_{p1} g_{p1}(x, y) & \dots & \sum_{pM=1}^{NM} B_{pM} g_{pM}(x, y) \end{pmatrix} \hat{Y} \begin{pmatrix} \sum_{q1=1}^{N1} B_{q1} g_{q1}(x, y) \\ \vdots \\ \sum_{qM=1}^{NM} B_{qM} g_{qM}(x, y) \end{pmatrix} \right\rangle \quad (25)$$

Matrix dispersion of the complete circuit is obtained by minimizing the expression (25) by B_{pi} .

The MMVF gives a characterization of all the modes of the entire structure in the case of simple discontinuities [19] between waveguides. It works on the idea of minimizing the variational and stationary function as follows: Being the matrix operator self-adjoint admittance of the structure complete, (19) denotes the scalar product, is the number of one discontinuities, and is the matrix operator self-adjoint admittance of the structure complete. The tangential electric field of the discontinuity can be decomposed on the modal basis of Eigen functions, which meets the boundary conditions, when we examine basic openings of (restrictions rectangle, circle, ellipse, etc...). When we contemplate the multiple openings that are difficult. The modal base of eigenfu's eigenfu's eigenfu's eigenfu's. The first-order interpolation function is chosen. The tangential electric field in the opening of between two neighboring elements can be expressed as follows: The unknown tangential-electric field along the edge EEP is denoted by the number of edges in the opening (22). We have two scenarios to find the (are new interpolation functions): The first is that if the pème edge is near the opening's edge, the coefficients play the same role in the connection as Cq (20). As a

result, they'll be thrown out. In the MVM elaboration (23). The second scenario is when the pème edge is It can only belong to two adjacent (e) components and (e') inside the opening. As a result, the edge will define two opposite-direction functions and interpolation. As a result, we get the following function by combining equations 19 and 21: (25) The whole circuit's matrix dispersion is derived by minimizing the expression (25) by. The number of edges in the discontinuities, which is distinct from the number of modes, determines the magnitude of the fundamental functions. As a result, we exclusively deal with dimension matrices.

4.2 Simulations Results

4.2.1 Discontinuity Constitutive M=1: iris shape cross

We consider an iris shape cross centered with rounded edges in a rectangular waveguide WR90 X-band. geometry and the mesh of the opening, the related susceptances of iris which inserted in two isotropic media ($\epsilon_r = 1, \mu_r = 1$) and ($\epsilon_r = 1,5, \mu_r = 1,5$) respectively. Where B and Y0 denote an opening cross susceptances and admittance characteristic respectively.

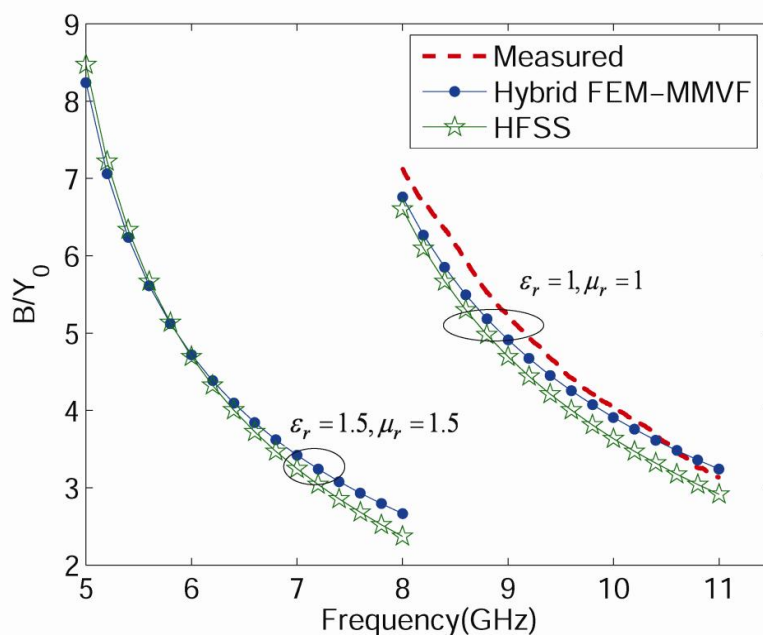


Fig. 1. The relative suscepance of the opening

We observe Fig. 1 the obtained results of method are well consistent by measurement and HFSS software. Nevertheless, the proposed hybrid method gives an overall reduction of convergence time more than 95% against HFSS in both cases. Studies of convergence of the results of our method against the number of items and the number of modes in the empty wave guide can be found in. If we compare calculation

between our hybrid method and HFSS time ($\epsilon_r = 1$, $\mu_r = 1$). We mention the discontinuity that a discontinuity for the GEF-sue hybrid and the hybrid FEM-MMVF are identical. In a rectangular waveguide WR90 X-band, we consider an iris shape cross that is centered and has rounded edges. The related susceptances of iris placed in the geometry and mesh of the opening and respectively, in two isotropic media. The opening cross susceptances and admission characteristic are denoted by the letters B and Y0, respectively. Fig.1. The opening's relative sensitivity. The observed outcomes, we notice, are The measurements and HFSS software agree nicely with our procedure. Nonetheless, the suggested hybrid technique achieves a reduction in overall. In both cases, the convergence time was greater than 95% compared to HFSS. The number of items and the number of modes in the empty wave guidance have been studied for convergence of our method's outcomes. When we compare our hybrid approach to the HFSS time, we can see that our hybrid method is more accurate. We highlight that the GEF-Sue hybrid and the hybrid FEM-MMVF have the same discontinuity.

4.2.2 Two Discontinuities one axis M=2: resonator filter

At a first step we find out a filter resonator filled isotropic medium (

$\epsilon_r = 1,3$, $\mu_r = 1,3$) built by two identical complex iris spaced a distance d, in second step, the geometry and the mesh of an iris. In order to the number of modes, we found in practice that the optimal way is first to arrange patterns by ascending cut of frequencies. Then, we placed a frequency F. Finally, we took all the modes with cut off frequencies smaller than F in all wave guides. A study of convergence we have F = 600 GHz. Discontinuities M=2 on one axis: resonator filter In the first phase, we discover a filter resonator filled isotropic media (,) composed of two identical complex iris separated by d, and in the

second step, we discover the geometry and mesh of an iris. In order to determine the number of modes, we discovered that the best method is to organize patterns by ascending cut off frequencies first. After that, we added a frequency F. Finally, we extracted all modes in all wave guides with cutoff frequencies less than F. F = 600 GHz is the result of a convergence investigation. The filter's reflection coefficient for d=17mm and d=8.5mm, respectively. By altering the number of accessible modes, the results achieved utilizing hybridization GEF-MMVF are compared to those obtained using HFSS and connecting matrices S. The reflection coefficient of filter for d= 17 mm and d= 8.5 mm respectively. The results obtained using hybridization GEF-MMVF are compared with those made by made by HFSS and linking matrices S by varying the number of available modes. In the simulations.

5. CONCLUSION

In this work, we introduced, for complex 2D discontinuities, a new hybrid modeling tool presented in cascade rectangular waveguides: we applied an S-parameter generalized analysis method for single. Tests were successfully accomplished with rectangular metallic waveguides presenting multiple one discontinuity and filled with both metamaterials isotropic or anisotropic. We conclude that convergence monitoring for several number for available modes can be omitted. We modulate a large complex structure such as multi-mode filters, using the new simulation tool. We applied generalized S- parameters method. To analyze complex discontinuities presented in rectangular waveguides, we suggest a hybrid method combining both vector finite element method and multimodal variational method. Because tangential electric field was formed in a first-order base of functions after the discontinuity surface was divided into several rectangular or triangular portions. When compared to EMF-based simulation (HFSS) tools, our hybrid technique FEM- utilizes to investigate a difficult discontinuity saves over 95% of the processing time while keeping the same precision. The new simulation tool was applied to modeling a complex iris filter and a dual-mode filter, in case its related speed compared simulated commercial simulated tools is highlighted.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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