Analysis of a Rectangular Waveguide T-junction with a 2D Inclusion via Green's Theorem

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***Abstract* — A rigorous method for solving 2D scattering by an arbitrary perfectly conducting inclusion located in the region of a rectangular waveguide T-junction is presented. This method is developed from the approach based on the Green's theorem. The latter is simultaneously the wave equation and the boundary conditions on the scatterer surface. The proposed method is illustrated by results obtained for a thick septum located inside the interaction region. Such approach can be applied for optimization of waveguide junctions.generalized using special weighting functions satisfying**

***Index Terms*— Waveguide Junctions, Green's Theorem, Microwave, Rectangular Waveguide.**

I. INTRODUCTION

The T-junction of two waveguides is an important element of waveguide tracts, which can be used as one of the key building blocks of various devices, e.g., power dividers, filters, multiplexers. The presence of extensive applications necessitates the development of methods for the study of such structures.

The paper presents a rigorous solution for a 2D scattering problem of electromagnetic wave by a perfectly conducting inclusion of an arbitrary cross section shape within an interaction region of rectangular waveguide T-junction. In Fig. 1 the interaction region is bounded by line segments L_0, L_1, L_2, L_3, and the scatterer surface L_S. This model can be applied for optimizing the transmission properties of waveguide junctions by placing rods or septums.

The approach proposed is based on the Green's theorem method, which has been previously successfully applied to characterization of different T-junctions of rectangular waveguides. E.g. in [1] the problem is solved using the appropriate integral equation of the residue theory and the weighting functions, which were chosen so as to identically satisfy Helmholtz equation in the inhomogeneous region of the waveguide junction. The characteristic feature of our approach is that we choose the weighting functions in such manner that they automatically take into account the presence of the perfectly electric conducting (PEC) inclusion. More precisely, the system of wave functions is found from solutions of the three auxiliary problems for scattering by the inclusion in short-circuited waveguides.

Manuscript received December 04, 2014.

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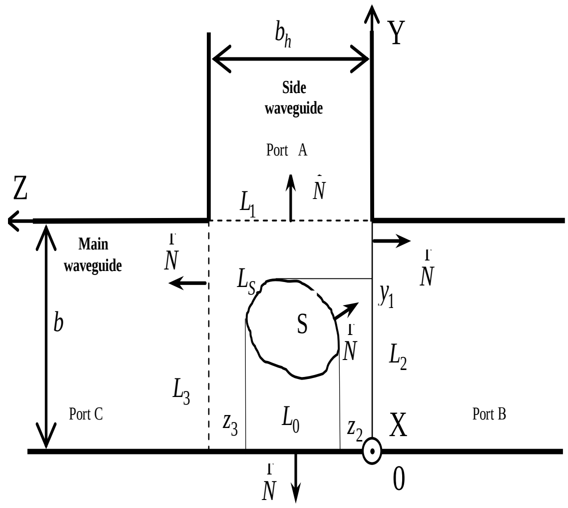


Fig. 1. The structure under study: rectangular waveguide T-junction containing a PEC scatterer.

A simple system of algebraic equations for determining the amplitudes of scattered fields in the waveguides can be obtained. To this aim only one propagating mode is taken into account in one of the waveguides and the scattering coefficients are found by using the three-short method [2, 3], which enables us to obtain the scattering coefficients with high accuracy. With this approach, one can construct the complete scattering matrix in a closed form for an arbitrary number of waveguide modes [4]. Thus, this paper presents the further development of the Green's theorem method for the case when the T-shaped interaction region of two variously sized rectangular waveguides is loaded with an E-plane perfectly conducting septum.

II. FORMULATION OF THE PROBLEM

For definiteness, we restrict our consideration to the analysis of LM waves in the E-plane of the waveguide junction [5]. The time dependence is assumed in the form $\exp(-i\omega \cdot t)$. For this type of waves the nonzero component $E_x(x, y, z)$ of the electric field can be presented in the following form:

$$E_x(x,y,z) = \cos\left(\frac{\pi m}{a} x\right) W(y,z). \quad (1)$$

The other projections of the electromagnetic field are written as follows:

$$E_y(\vec{R}) = -\frac{\pi m/a}{k^2-(\pi m/a)^2}\sin\left(\frac{\pi m}{a}x\right)\partial_y W(y,z),$$

$$E_z(\vec{R}) = -\frac{\pi m/a}{k^2-(\pi m/a)^2}\sin\left(\frac{\pi m}{a}x\right)\partial_z W(y,z),$$

$$H_x(\vec{R}) = 0,$$

$$H_y(\vec{R}) = -\frac{i\omega}{k^2-(\pi m/a)^2}\cos\left(\frac{\pi m}{a}x\right)\partial_z W(y,z),$$

$$H_z(\vec{R}) = \frac{i\omega}{k^2-(\pi m/a)^2}\cos\left(\frac{\pi m}{a}x\right)\partial_y W(y,z),$$

where a is the common dimension of the waveguides. We assume that the $x-$ mode order $m=0,1,2,...$ is fixed. Function $W(y,z)$ satisfies the Helmholtz equation

$$(\Delta_{y,z}+K^2)W(y,z)=0, \quad (2)$$

and zero boundary conditions on the PEC walls of the waveguide and contour L_S of the scatterer S. Here, $K=[k^2-(\pi m/a)^2]^{1/2}$ is the effective wavenumber, k is the wavenumber of the waveguide filling. In regular regions $A\,(y>b)$, $B\,(z<0)$ and $C\,(z>b_h)$, function $W(y,z)$ is represented as

$$W^A = \sum_{n=1}^{+\infty}\left\{A_n^{in}\exp[-i\eta_n(y-b)]+A_n^{sc}\exp[i\eta_n(y-b)]\right\}\sin\left(\frac{\pi n}{b_h}z\right),$$

$$W^B = \sum_{n=1}^{+\infty}\left\{B_n^{in}\exp[i\beta_n z]+B_n^{sc}\exp[-i\beta_n z]\right\}\sin\left(\frac{\pi n}{b}y\right), \quad (3)$$

$$W^C = \sum_{n=1}^{+\infty}\left\{C_n^{in}\exp[-i\beta_n(z-b_h)]+C_n^{sc}\exp[i\beta_n(z-b_h)]\right\}\sin\left(\frac{\pi n}{b}y\right),$$

where $A_n^{in}, B_n^{in}, C_n^{in}$ and $A_n^{sc}, B_n^{sc}, C_n^{sc}$ are the amplitude coefficients of the incident and scattered waves; $\eta_n=[K^2-(\pi n/b_h)^2]^{1/2}$ and $\beta_n=[K^2-(\pi n/b)^2]^{1/2}$ are the longitudinal wavenumbers of the respective waveguides.

It is necessary to define the scattering matrix elements $\mathbf{SIJ}\ (\mathbf{I},\mathbf{J}=\mathbf{A},\mathbf{B},\mathbf{C})$, which are determined as

$$\mathbf{A^{sc}} = \mathbf{SAA}\cdot\mathbf{A^{in}}+\mathbf{SAB}\cdot\mathbf{B^{in}}+\mathbf{SAC}\cdot\mathbf{C^{in}},$$
$$\mathbf{B^{sc}} = \mathbf{SBA}\cdot\mathbf{A^{in}}+\mathbf{SBB}\cdot\mathbf{B^{in}}+\mathbf{SBC}\cdot\mathbf{C^{in}}, \quad (3)$$
$$\mathbf{C^{sc}} = \mathbf{SCA}\cdot\mathbf{A^{in}}+\mathbf{SCB}\cdot\mathbf{B^{in}}+\mathbf{SCC}\cdot\mathbf{C^{in}}.$$

Here we introduce the column vectors of the amplitudes of the incident and scattered waves $\mathbf{A^{in}}=\{A_n^{in}\}$, $\mathbf{B^{in}}=\{B_n^{in}\}$, $\mathbf{C^{in}}=\{C_n^{in}\}$; $\mathbf{A^{sc}}=\{A_n^{sc}\}$, $\mathbf{B^{sc}}=\{B_n^{sc}\}$, $\mathbf{C^{sc}}=\{C_n^{sc}\}$.

Let's introduce a solution to equation (3) in the inhomogeneous region $\tilde{W}(x,y)$ that satisfies zero boundary conditions on the PEC surfaces:

$$\tilde{W}\big|_{L_S}=0;\quad \tilde{W}\big|_{L_0}=0, \quad (4)$$

Next we transform Helmholtz equation (3) inside the inhomogeneous region into the integral equation over the contour $L=L_0+L_1+L_2+L_3+L_s$ of the said region by applying the second Green's formula [6]:

$$\int_L dL\left(\tilde{W}\frac{\partial W}{\partial N}-W\frac{\partial\tilde{W}}{\partial N}\right)=0, \quad (5)$$

where $W(y,z)$, as before, is an arbitrary solution to Eq. (3) in the inhomogeneous region and $\partial/\partial N$ denotes the normal derivative at contour L. As $\tilde{W}$ we consecutively substitute the three solutions of the auxiliary problems for the main and the side (see Fig. 1) waveguides.

Taking into account the boundary conditions (5) on the perfectly conducting segments L_0 and L_s of the integration contour the latter expression yields:

$$\int_{L_1+L_2+L_3} dL\left(\tilde{W}\frac{\partial W}{\partial N}-W\frac{\partial\tilde{W}}{\partial N}\right)=0. \quad (6)$$

Next, we particularize our model and consider first the auxiliary problem, which represents the main waveguide containing the scatterer S in the form of a rectangular septum (see Fig. 2a). This model can formally be obtained from the structure presented in Fig. 1 if we consider the upper section of line L_1 to be PEC. Let the scatterer in this auxiliary waveguide is excited by the mode of order $q=1,2,...$ propagating from $z=-\infty$ (port B). In this case, solution outside the scatterer $\tilde{W}(y,z)\equiv\tilde{W}_q^B(y,z)$ in region $z_3<z<z_2$ is

$$\tilde{W}_q^B(y,z)=\begin{cases}\tilde{W}_B^{in}+\tilde{W}_{BB}^{sc},\ z<z_2,\\ \tilde{W}_{CB}^{sc},\ z>z_3,\end{cases}. \quad (7)$$

in equation (7) we have introduced the following notations for the waves:

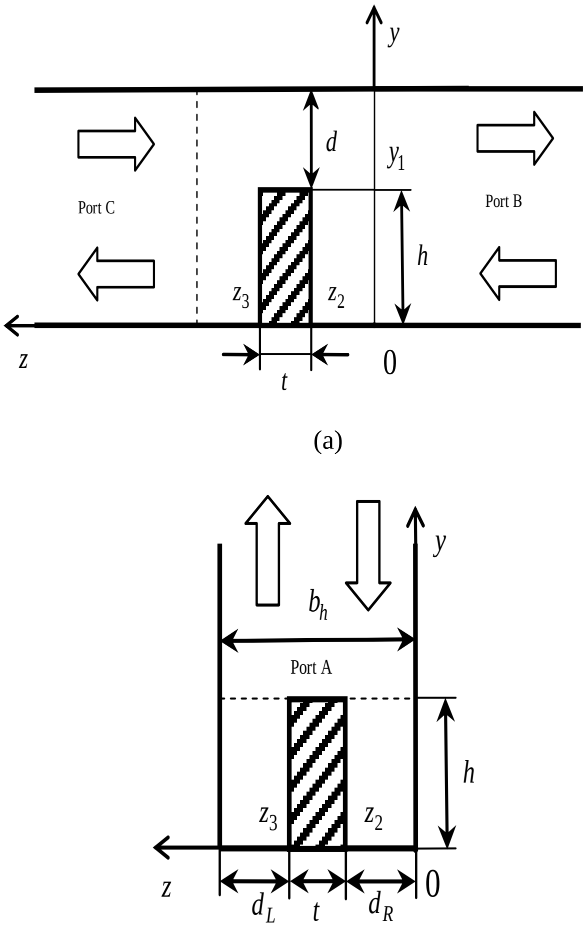
$$\tilde{W}_B^{in}=\exp[i\beta_q(z-z_2)]\sin\left(\frac{\pi q}{b}y\right),\quad z<z_2,$$

$$\tilde{W}_{BB}^{sc}=\sum_{s=0}^{+\infty}S_{sq}^{BB}\exp[-i\beta_s(z-z_2)]\sin\left(\frac{\pi s}{b}y\right),\quad z<z_2, \quad (8)$$

$$\tilde{W}_{CB}^{sc}=\sum_{s=0}^{+\infty}S_{sq}^{CB}\exp[i\beta_s(z-z_3)]\sin\left(\frac{\pi s}{b}y\right),\quad z>z_3.$$

As the second auxiliary problem, we consider the same main waveguide, but now assuming that the waveguide is excited by the mode of order $q=1,2,...$ propagating from $z=+\infty$ (port C). The solution outside the scatterer $\tilde{W}(y,z)\equiv \tilde{W}_q^C(y,z)$ looks like

$$\tilde{W}_q^C(y,z)=\begin{cases}\tilde{W}_C^{in}+\tilde{W}_{CC}^{sc},\ z>z_3,\\ \tilde{W}_{BC}^{sc},\ z<z_2,\end{cases} \qquad (9)$$



(a)

(b)

Fig. 2. The auxiliary structures: for the first and the second auxiliary problems (a); for the third auxiliary problem (b)

where

$$\tilde{W}_C^{in}=\exp[-i\beta_q(z-z_3)]\sin\left(\frac{\pi q}{b}y\right),\quad z>z_3,$$

$$\tilde{W}_{CC}^{sc}=\sum_{s=1}^{+\infty}S_{sq}^{CC}\exp[i\beta_s(z-z_3)]\sin\left(\frac{\pi s}{b}y\right),\quad z>z_3,\qquad (10)$$

$$\tilde{W}_{BC}^{sc}=\sum_{s=1}^{+\infty}S_{sq}^{BC}\exp[-i\beta_s(z-z_2)]\sin\left(\frac{\pi s}{b}y\right),\quad z<z_2.$$

The third auxiliary problem is formulated for the structure formally obtained from Fig. 1 if the segments L_2 and L_3 are assumed to be PEC (see Fig. 2b). Let the wave of mode order $q=1,2,...$ propagates from the side $y=+\infty$ (port A). In this case the solution outside the scatterer $\tilde{W}(y,z)\equiv \tilde{W}_q^A(y,z)$ for the region $y>y_1$ can be written in the form

$$\tilde{W}_q^A(y,z)=\begin{cases}\tilde{W}_A^{in}+\tilde{W}_{AA}^{sc},\ y>y_1,\\ \tilde{W},\ 0<y<y_1.\end{cases}\qquad (11)$$

Here

$$\tilde{W}_A^{in}=\exp[-i\eta_q(y-y_1)]\sin\left(\frac{\pi q}{b_h}z\right),\quad y>y_1,$$

$$\tilde{W}_{AA}^{sc}=\sum_{s=1}^{+\infty}S_{sq}^{AA}\exp[i\eta_s(y-y_1)]\sin\left(\frac{\pi s}{b_h}z\right),\quad y>y_1. \qquad (12)$$

Note that in (8), (10), and (12) S^{IJ} $(I,J=A,B,C)$ are elements of the scattering matrices, which are defined during the auxiliary problems solution.

Here we introduce the column vectors of the incident and scattered waves amplitudes: $\mathbf{A^{in}}=\{A_n^{in}\}$, $\mathbf{B^{in}}=\{B_n^{in}\}$, $\mathbf{C^{in}}=\{C_n^{in}\}$; $\mathbf{A^{sc}}=\{A_n^{sc}\}$, $\mathbf{B^{sc}}=\{B_n^{sc}\}$, $\mathbf{C^{sc}}=\{C_n^{sc}\}$. The scattering coefficients and the solutions of the auxiliary problems can be found using various numerical techniques, such as the mode-matching method [7], boundary contour mode-matching method [8], the moment procedure [9, 10]. Here we use mode-matching method in the partial domains with PEC boundary conditions at the metal surfaces and continuity conditions for $\tilde{W}(y,z)$ and its normal derivative either $\partial\tilde{W}/\partial z$ or $\partial\tilde{W}/\partial y$ on the relevant apertures.

Next, we substitute the found weight functions $\tilde{W}_q^A(y,z)$, $\tilde{W}_q^B(y,z)$, $\tilde{W}_q^C(y,z)$ to the second Green's formula (6) in place of $\tilde{W}$ and take into account the explicit form (4) for $W(y,z)$ in each of the interaction regions and impose the boundary conditions for W and $\tilde{W}$ on the PEC surfaces. As a result we arrive to a direct formula for calculating the scattering amplitudes A_n^{sc}, B_n^{sc}, C_n^{sc}:

$$A_q^{sc}=\sum_{n=1}^{+\infty}[R_{qn}^A\cdot A_n^{in}+R_{qn}^B\cdot(B_n^{in}+B_n^{sc})+R_{qn}^C\cdot(C_n^{in}+C_n^{sc})],$$

$$B_q^{sc}=\sum_{n=1}^{+\infty}[P_{qn}^A\cdot(A_n^{in}+A_n^{sc})+P_{qn}^B\cdot B_n^{in}+P_{qn}^C\cdot C_n^{in}],\qquad (13)$$

$$C_q^{sc}=\sum_{n=1}^{+\infty}[Q_{qn}^A\cdot(A_n^{in}+A_n^{sc})+Q_{qn}^B\cdot B_n^{in}+Q_{qn}^C\cdot C_n^{in}],$$

where $q=1,2,...$, and the matrix coefficients have the form:

$$R_{qn}^A=\frac{\exp[i\eta_q(b-y_1)]}{\eta_q}\eta_n\exp[i\eta_n(b-y_1)]\cdot S_{nq}^{AA},$$

$$R_{qn}^B=-\frac{b^2}{2b_h i}GW_{qn}^{AB},$$

$$GW_{qn}^{AB} = \frac{2\exp[i\eta_q(b-y_1)]}{\eta_q b^2} \int_0^b \left. \frac{\partial \tilde{W}_q^A(y,z)}{\partial z} \right|_{z=0} \sin\left(\frac{\pi n}{b} y\right) dy,$$

$$R_{qn}^C = \frac{b^2}{2b_h i} GW_{qn}^{AC},$$

$$GW_{qn}^{AC} = \frac{2\exp[i\eta_q(b-y_1)]}{\eta_q b^2} \int_0^b \left. \frac{\partial \tilde{W}_q^A(y,z)}{\partial z} \right|_{z=b_h} \sin\left(\frac{\pi n}{b} y\right) dy,$$

$$P_{qn}^A = \frac{b_h^2}{2bi} GW_{qn}^B,$$

$$GW_{qn}^B = \frac{2\exp[i\beta_q z_2]}{\beta_q b_h^2} \int_0^{b_h} \left. \frac{\partial \tilde{W}_q^B(y,z)}{\partial y} \right|_{y=b} \sin\left(\frac{\pi n}{b_h} z\right) dz,$$

$$P_{qn}^B = \frac{\exp[i\beta_q z_2]}{\beta_q} \beta_n \exp[i\beta_n z_2] \cdot S_{nq}^{BB},$$

$$P_{qn}^C = \frac{\exp[i\beta_q z_2]}{\beta_q} \beta_n \exp[i\beta_n (b_h - z_3)] \cdot S_{nq}^{CB},$$

$$Q_{qn}^A = \frac{b_h^2}{2bi} GW_{qn}^C,$$

$$GW_{qn}^C = \frac{2\exp[i\beta_q(b_h-z_3)]}{\beta_q b_h^2} \int_0^{b_h} \left. \frac{\partial \tilde{W}_q^C(y,z)}{\partial y} \right|_{y=b} \sin\left(\frac{\pi n}{b_h} z\right) dz,$$

$$Q_{qn}^B = \frac{\exp[i\beta_q(b_h - z_3)]}{\beta_q} \beta_n \exp[i\beta_n z_2] \cdot S_{nq}^{BC},$$

$$Q_{qn}^C = \frac{\exp[i\beta_q(b_h - z_3)]}{\beta_q} \beta_n \exp[i\beta_n (b_h - z_3)] \cdot S_{nq}^{CC}.$$

The integrals on the right hand sides of the above expressions can be calculated in a closed form provided that $\tilde{W}_q^A, \tilde{W}_q^B, \tilde{W}_q^C$ are known.

Next we substitute the second and third equations from (14) into the first equation thus eliminating $\{B_n^{sc}\}$ and $\{C_n^{sc}\}$. As a result we obtain the system of linear algebraic equations (SLAE) for the amplitudes of the scattered field in the side waveguide $\mathbf{A^{sc}} = \{A_n^{sc}\}$, which in matrix form looks like

$$(\mathbf{I}-\mathbf{D}) \cdot \mathbf{A^{sc}} = \mathbf{U^A} \cdot \mathbf{A^{in}} + \mathbf{U^B} \cdot \mathbf{B^{in}} + \mathbf{U^C} \cdot \mathbf{C^{in}}. \quad (14)$$

Here $\mathbf{I}$ – is identity matrix, and the other matrices appearing in (15) are defined as follows

$$\mathbf{D} = \mathbf{R^B} \cdot \mathbf{P^A} + \mathbf{R^C} \cdot \mathbf{Q^A},$$
$$\mathbf{U^A} = \mathbf{R^A} + \mathbf{R^B} \cdot \mathbf{P^A} + \mathbf{R^C} \cdot \mathbf{Q^A},$$
$$\mathbf{U^B} = \mathbf{R^B} + \mathbf{R^B} \cdot \mathbf{P^B} + \mathbf{R^C} \cdot \mathbf{Q^B},$$
$$\mathbf{U^C} = \mathbf{R^C} + \mathbf{R^B} \cdot \mathbf{P^C} + \mathbf{R^C} \cdot \mathbf{Q^C}.$$

The solution to SLAE (15) can be written in the form:

$$\mathbf{A^{sc}} = (\mathbf{I}-\mathbf{D})^{-1} \cdot (\mathbf{U^A} \cdot \mathbf{A^{in}} + \mathbf{U^B} \cdot \mathbf{B^{in}} + \mathbf{U^C} \cdot \mathbf{C^{in}}). \quad (15)$$

Comparing the solution (16) with the definition of the scattering matrix (13), we find expressions for the scattering matrix elements in the side waveguide $A\,(y > b)$

$$\mathbf{S^{AA}} = (\mathbf{I}-\mathbf{D})^{-1} \cdot \mathbf{U^A},$$
$$\mathbf{S^{AB}} = (\mathbf{I}-\mathbf{D})^{-1} \cdot \mathbf{U^B}, \quad (16)$$
$$\mathbf{S^{AC}} = (\mathbf{I}-\mathbf{D})^{-1} \cdot \mathbf{U^C}.$$

Using direct formulae (14-17) we obtain the elements of the scattering matrix in the main waveguide:

- for scattering in port B of the main waveguide ($z < 0$)

$$\mathbf{S^{BA}} = \mathbf{P^A} \cdot (\mathbf{I} - \mathbf{S^{AA}}),$$
$$\mathbf{S^{BB}} = \mathbf{P^B} - \mathbf{P^A} \cdot \mathbf{S^{AB}}, \quad (17)$$
$$\mathbf{S^{BC}} = \mathbf{P^C} - \mathbf{P^A} \cdot \mathbf{S^{AC}},$$

- for scattering in port C of the main waveguide ($z > b_h$)

$$\mathbf{S^{CA}} = \mathbf{Q^A} \cdot (\mathbf{I} - \mathbf{S^{AA}}),$$
$$\mathbf{S^{CB}} = \mathbf{Q^B} - \mathbf{Q^A} \cdot \mathbf{S^{AB}}, \quad (18)$$
$$\mathbf{S^{CC}} = \mathbf{Q^C} - \mathbf{Q^A} \cdot \mathbf{S^{AC}}.$$

III. NUMERICAL EXAMPLES

Let us consider a PEC rectangular septum of thickness t and height h, placed in the interaction region of the empty waveguides and, to be specific, fixed to the downside wall of the main waveguide (see insert in Fig. 3). We are interested in the complex elements of the scattering matrix $S^{IJ}(I,J = A,B,C)$. The waveguide dimensions are $a = 8.64\,cm$, $b = b_h = a/2$. Figs. 3, 4 illustrate frequency dependence of the reflection coefficient for LM_{01} impinged from the port A for various geometric parameters of the inclusion. In these figures the septum is placed symmetrically in the interaction region along the z-axis.

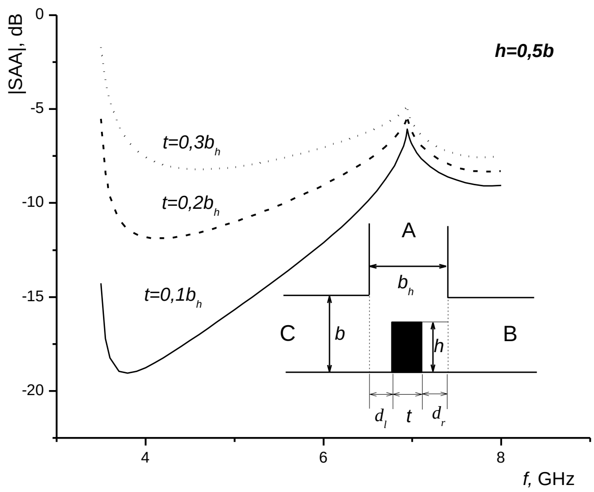


Fig. 3. The reflection coefficient for LM_{01}-mode at port A for different t.

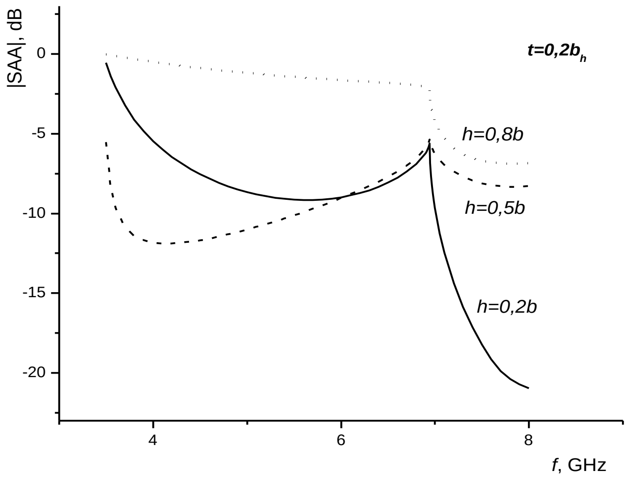


Fig. 4. The reflection coefficient for LM_{01} -mode at port A for different h .

The results of comparison of the scattering parameters in the cases of symmetrical (solid line) and asymmetrical (dash line) septum position in the interaction region are presented in Figs. 5, 6. The step dimensions were chosen as $h = 0,5b$, $t = 0,2b_h$.

Correctness of the numerical simulation was monitored by checking the balance of power in the ports of the T-junction. Accuracy of 10^{-8} was achieved in the considered frequency band using 12 modes. It takes less than a second to compute 100 frequency points using the proposed method. The accuracy of the results those obtained by Ansoft HFSS is of the order $10^{-2}...10^{-3}$ and the computation time is of order 30-50 s. The algorithm allocates memory for about 20 complex matrices of size 12x12.

The results obtained by our method are compared with the data those obtained by Ansoft HFSS. Agreement within the bounds of HFSS method accuracy is achieved for all the considered cases.

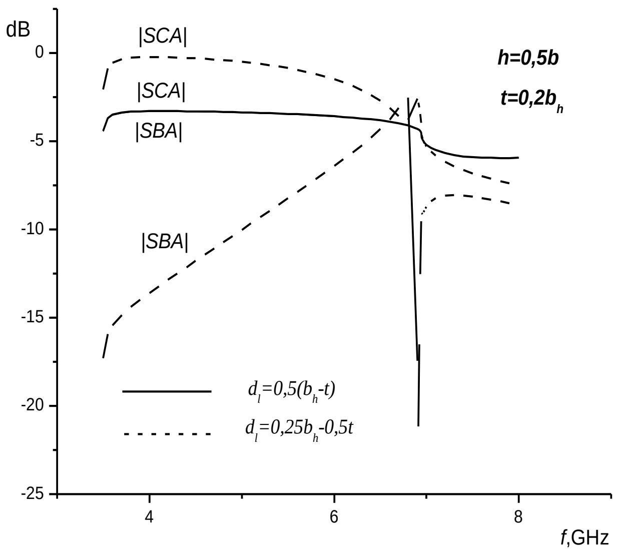


Fig. 5. Transition coefficients into ports B, C for different septum positions

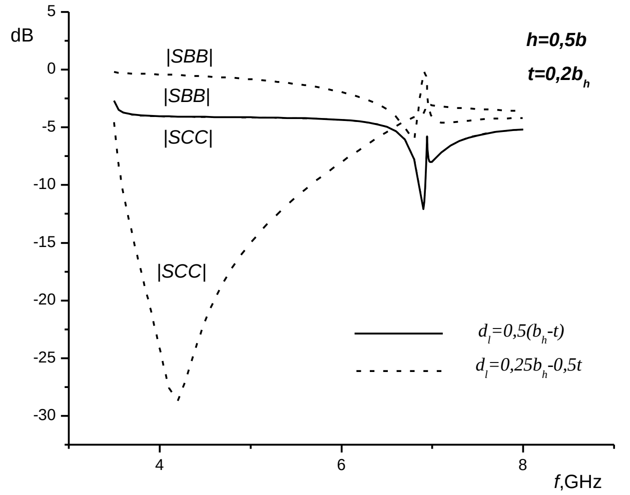


Fig. 6. Reflection coefficients for ports B, C for different septum positions.

IV. CONCLUSIONS

A universal method of rigorous analysis of metallic inclusions of arbitrary cross-section located in the interaction region of waveguide T-junction is proposed. This model can be used to optimize scattering properties of wave guide devices using rods or septums placed in waveguide junctions.

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