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ELECTROMAGNETIC OPTIMIZATION OF AN H-PLANE RESONATOR FILTER: A TRUST REGION AGGRESSIVE SPACE MAPPING APPROACH

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Abstract

Direct electromagnetic optimization of 3D passive microwave structures is computationally intensive. The Space Mapping (SM) technique provides a way to make it more efficient. In this report, the TRASM algorithm is applied to optimize an H-plane resonator filter. It aligns a mode-matching based coarse model with a finite element based fine model. The result is obtained after six fine model simulations. TRASM optimization of the H-plane resonator filter with rounded corners illustrates the advantages as well as the challenges of the approach.

I. INTRODUCTION

Aggressive Space Mapping (ASM) optimization [1] provides an efficient approach to optimize computationally intensive electromagnetic problems. It combines the accuracy of an electromagnetic based “fine” model with the speed of an empirical “coarse” model. ASM technique aims at searching the corresponding fine model aggressively. The fine model has the same response with the optimal response of the coarse model. Parameter extraction plays an important role in ASM. It extracts a set of coarse model parameters whose response matches a given fine model response. In general, parameter extraction

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is formulated into a classical optimization problem in SM. The result of this optimization problem may not be unique [2]. On the other hand, recent investigation [2] shows that multipoint parameter extraction could improve the uniqueness of the extraction procedure.

The TRASM algorithm [3] was proposed to automate multipoint parameter extraction. Trust region methodologies [4] have been used widely in nonlinear optimization as a robust method. Starting from an arbitrary initial point, the algorithm converges to a stationary point or local optimizer for the original problem.

In this report, the electromagnetic optimization of an H-plane waveguide filter [2] is reconsidered and solved by the TRASM algorithm. In [2], the problem had been solved by ASM. In order to make parameter extraction more reliable, a statistical approach was adopted. The statistical parameter extraction repeats parameter extraction from random starting points. Differing from the method used in [2], multipoint parameter extraction in TRASM is realized by an iterative approach that utilizes all fine model simulations. Hence, it is more efficient than the statistical approach to some extent.

The optimization problem is described in Section II and also the coarse and fine models are given. In Section III, the optimal coarse model parameters and response are obtained using minimax optimizer. The TRASM algorithm is applied successfully to the optimization of the H-plane resonator filter. Finally, the conclusions are given in Section IV.

II. THE COARSE AND FINE MODELS OF THE H-PLANE RESONATOR FILTER

The H-plane resonator filter with rounded corners is shown in Fig. 1 and Fig.2. The type of the utilized waveguide is WR62. The recommended frequency range is from 12.4 GHz to 18.0 GHz [5]. The waveguide cross-section is 15.8×7.9 mm, and the thickness of the irises is $t=0.4$ mm. The radius of the corners is $R=1$ mm. The iris and resonator dimensions d_1 , d_2 , l_1 and l_2 are optimized so that the scattering parameters meet the specifications [2]

$$|S_{21}| \leq -35 \text{ dB for } 13.5 \text{ GHz} \leq f \leq 13.6 \text{ GHz} \quad (1a)$$

$$|S_{11}| \leq -20 \text{ dB for } 14.0 \text{ GHz} \leq f \leq 14.2 \text{ GHz} \quad (1b)$$

$$|S_{21}| \leq -35 \text{ dB for } 14.6 \text{ GHz} \leq f \leq 14.8 \text{ GHz} \quad (1c)$$

SM optimization involves two models, the coarse and fine models. The coarse model should be fast. It is also a crucial part in SM optimization.

There are three ways to establish a coarse model for the H-plane resonator filter. The first one is an equivalent circuit model [6]. Each H-plane discontinuity (iris) in the uniform waveguide can be characterized by a shunt inductor [7, 8]. The value of the lumped inductor can be calculated directly from the dimensions of the discontinuity. Connecting these lumped inductors by dispersive transmission lines, the equivalent circuit model for the whole structure can be implemented. The second way is to utilize a coarse grid EM model. The third one is an approximate analytical model [2]. A regularly shaped structure is used to approximate the original structure so that it can be simulated analytically. However, the approximation must be able to exhibit the principal characteristics of the fine model. In [2], the H-plane resonator filter with square corners was taken as the coarse model. Thus, the MM/network theory can be used to simulate it analytically. Meanwhile, the approximation cannot lead to an evident error.

Just as it is described in [2], the H-plane resonator filter with square corners is also taken as the coarse model here. However, the mode-matching method [9] implemented by Matlab [10] is employed to simulate the coarse model. Differing from MM/network theory, the mode-matching method utilized is based on electric field \mathbf{E} and magnetic field \mathbf{H} instead of Hertzian vector potential. The mode-matching method is based on the fact that the fields in each waveguide section can be expanded in terms of an orthogonal set of transverse modal field solutions. The coefficients of each mode can be computed by applying the tangential continuity conditions of \mathbf{E} and \mathbf{H} at each discontinuous aperture.

The Finite Element Method (FEM) is a generalized electromagnetic field solver with high accuracy. But it is computationally intensive. In this report, HP HFSS [11] is used as the fine model.

III. SPACE MAPPING OPTIMIZATION

A. Optimization of the Coarse Model Using Minimax

First, optimization of the coarse model is performed by exploiting the minimax optimizer in the Matlab optimization toolbox. The optimal response is shown in Fig. 3. This response is the target response for SM. The optimal coarse model parameters are $d_1=5.93988$ mm, $d_2=3.09090$ mm, $l_1=13.0457$ mm and $l_2=13.8856$ mm. It should be mentioned that the number of modes in different regions are 10 modes in the uniform waveguide, 8 modes in the first and fourth irises and 6 modes in the second and third irises.

B. TRASM [3] Approach to Optimization of the H-Plane Resonator Filter

The steps of the successful TRASM optimization, including fine model simulations and parameter extractions, are given in Table I and Table II, respectively. Correspondingly, the fine model simulation results are shown in Fig. 4 in sequence. Comparing the optimal coarse model response with the fine model response at \mathbf{x}_{os}^* , we observe a severe violation in the passband. TRASM obtains the space-mapped design using only six fine model simulations. The final response of the fine model matches the optimal coarse model response very well. They are shown in Fig. 5. It takes several minutes (3-4 minutes) to simulate the fine model using fast frequency sweep technique in HP HFSS, whereas only a few seconds (3-4 s) are needed for one coarse model simulation.

At each parameter extraction step, it is found that the response of extracted coarse model matches the corresponding fine model response very well. For instance, the coarse model responses before and after parameter extraction in the first iteration are shown in Fig. 6. It shows that for any response of a fine model whose parameters are confined in a bounded region, one always can find a set of parameters of a coarse model (probably nonunique) whose response matches the response.

IV. CONCLUSIONS

Electromagnetic optimization of the H-plane resonator filter has been solved successfully by the TRASM optimization method. The final fine model response is very close to the optimal coarse model

response. Using only six fine model simulations, the TRASM algorithm finds a set of fine model parameters corresponding to \mathbf{x}_{os}^* .

On the other hand, the mode-matching method based electromagnetic model provides a good coarse model for space mapping optimization. It is fast and accurate enough to exhibit the principal characteristics of the physical model. The physical and mathematical investigations on the topological structure of coarse model space and fine model space, especially their mapping relationship, are very interesting topics in SM optimization and need further study.

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APPENDIX

THE SETUP OF THE H-PLANE RESONATOR FILTER IN HFSS

A. File Name and Path

In this report, finite element method based HP HFSS is used as the fine model simulator. Totally, six fine model simulations are needed. Correspondingly, they are saved as HP HFSS project files. These project files are listed in Table III.

B. Main Steps To Construct The H-plane Resonator Filter

According to the symmetry of the structure, only TE_{n0} modes, for n odd, will be excited [5]. So only a quarter of the whole structure needs to be simulated.

Step 1. Decompose the whole structure into a set of components that can be drawn in HP HFSS. In this case, they are a uniform waveguide and four irises with rounded corners.

Step 2. Determine the coordinates of each component carefully. Since there is not a ready made component for the iris with rounded corners in HP HFSS, we need to construct it by sweeping the cross section of the discontinuity. The cross section can be obtained by connecting arcs and straight lines. Equations (2a – 2n) are given to determine the coordinates of these points utilized to draw polylines and arcs (point B , G , J and O). These points are shown in Fig. 8. The other two irises can be constructed in the similar way.

$$\text{Point A: } x_A = -\left(l_1 + \frac{l_2}{2} + 2t + R\right), \quad y_A = \frac{w_1}{2} \quad (2a)$$

$$\text{Point B: } x_B = -\left(l_1 + \frac{l_2}{2} + 2t + R\right), \quad y_B = \frac{w_1}{2} - R \quad (2b)$$

$$\text{Point C: } x_C = -\left(l_1 + \frac{l_2}{2} + 2t\right), \quad y_C = \frac{w_1}{2} - R \quad (2c)$$

$$\text{Point D: } x_D = -\left(l_1 + \frac{l_2}{2} + 2t\right), \quad y_D = \frac{d_1}{2} \quad (2d)$$

$$\text{Point } E: \quad x_E = -\left(l_1 + \frac{l_2}{2} + t\right), \quad y_E = \frac{d_1}{2} \quad (2e)$$

$$\text{Point } F: \quad x_F = -\left(l_1 + \frac{l_2}{2} + t\right), \quad y_F = \frac{w_1}{2} - R \quad (2f)$$

$$\text{Point } G: \quad x_G = -\left(l_1 + \frac{l_2}{2} + t - R\right), \quad y_G = \frac{w_1}{2} - R \quad (2g)$$

$$\text{Point } H: \quad x_H = -\left(l_1 + \frac{l_2}{2} + t - R\right), \quad y_H = \frac{w_1}{2} \quad (2h)$$

$$\text{Point } I: \quad x_I = -\left(\frac{l_2}{2} + t + R\right), \quad y_I = \frac{w_1}{2} \quad (2i)$$

$$\text{Point } J: \quad x_J = -\left(\frac{l_2}{2} + t + R\right), \quad y_J = \frac{w_1}{2} - R \quad (2j)$$

$$\text{Point } K: \quad x_K = -\left(\frac{l_2}{2} + t\right), \quad y_K = \frac{w_1}{2} - R \quad (2k)$$

$$\text{Point } L: \quad x_L = -\left(\frac{l_2}{2} + t\right), \quad y_L = \frac{d_2}{2} \quad (2l)$$

$$\text{Point } M: \quad x_M = -\left(\frac{l_2}{2}\right), \quad y_M = \frac{d_2}{2} \quad (2m)$$

$$\text{Point } N: \quad x_N = -\left(\frac{l_2}{2}\right), \quad y_N = \frac{w_1}{2} - R \quad (2n)$$

$$\text{Point } O: \quad x_O = -\left(\frac{l_2}{2} - R\right), \quad y_O = \frac{w_1}{2} - R \quad (2o)$$

$$\text{Point } P: \quad x_P = -\left(\frac{l_2}{2} - R\right), \quad y_P = \frac{w_1}{2} \quad (2p)$$

where w_1 is the width of the waveguide.

Step 3. Draw a box as the uniform waveguide.

The geometry of the H-plane resonator filter is shown in Fig. 7. Next, each object is assigned to be a certain kind of material.

C. Material Attribute of Each Object and Boundary Conditions

The box representing the uniform waveguide is filled with air. The irises are defined to be metallic.

To carry out electromagnetic simulation, the appropriate boundary conditions are applied to the following six planes. They are port 1 (plane *abcd* in Fig. 7) whose scaled impedance is 1, port 2 (plane *efgh*) whose scaled impedance is 1, plane *bcgf* which is a symmetry H plane, plane *dcgh* which is a symmetry E plane, plane *adhe* and *abfe* which are perfect conductive planes. Taking advantage of symmetry planes can simplify simulation and reduce simulation run times.

D. Set Up A Simulation

Adaptive mesh refinement is enabled. The stopping criterion “Delta error” is 0.006 in the simulations. It means that the mesh refinement will stop if the magnitude of the vector difference for all *S*-parameters for two consecutive simulations is smaller than 0.006. The mesh refinement is performed at the highest frequency in the simulation, which is also recommended by HP HFSS.

Fast Frequency Sweep in HP HFSS Version 5.4 evaluates the *S*-parameter quickly for a large number of frequency points using the simulation results at single or several frequency points. Fast frequency sweep is enabled in the simulations, the frequency range is from 13.5 GHz to 14.8 GHz. The number of Max. # Freq. is 5, which is the maximum number of frequencies where solutions will be computed. The simulation results show that single frequency sweep can converge and provide accurate results in this case. By default, the fast frequency sweep begins at the midpoint of the frequency range.

TABLE I
EM SIMULATIONS FOR TRASM OPTIMIZATION

Point	d_1	d_2	l_1	l_2
$\mathbf{x}_{em}^{(1)}$	5.93988	3.09090	13.0457	13.8856
$\mathbf{x}_{em}^{(2)}$	6.32005	3.36897	13.0292	13.8869
$\mathbf{x}_{em}^{(3)}$	6.29002	3.33724	13.0360	13.8839
$\mathbf{x}_{em}^{(4)}$	6.28718	3.40526	13.0334	13.8879
$\mathbf{x}_{em}^{(5)}$	6.29070	3.39181	13.0314	13.8838
$\mathbf{x}_{em}^{(6)}$	6.28547	3.38211	13.0331	13.8849

values are in millimeters

TABLE II
PARAMETER EXTRACTIONS FOR TRASM OPTIMIZATION

Point	d_1	d_2	l_1	l_2
$\mathbf{x}_{os}^{(1)}$	5.58623	2.80657	13.0556	13.8872
$\mathbf{x}_{os}^{(2)}$	5.94247	3.05891	13.0482	13.8817
$\mathbf{x}_{os}^{(3)}$	5.93391	3.11374	13.0492	13.8926
$\mathbf{x}_{os}^{(4)}$	5.94241	3.10135	13.0453	13.8861
$\mathbf{x}_{os}^{(5)}$	5.94241	3.10135	13.0453	13.8861

values are in millimeters

TABLE III
FILES NAME AND PATH OF THE FINE MODEL PROJECTS

Point	File name and path
$\mathbf{x}_{em}^{(1)}$	c:\guofei\HPHFSS\hpf1086_1
$\mathbf{x}_{em}^{(2)}$	c:\guofei\HPHFSS\hpf1086_2
$\mathbf{x}_{em}^{(3)}$	c:\guofei\HPHFSS\hpf1086_3
$\mathbf{x}_{em}^{(4)}$	c:\guofei\HPHFSS\hpf1086_4
$\mathbf{x}_{em}^{(5)}$	c:\guofei\HPHFSS\hpf1086_5
$\mathbf{x}_{em}^{(6)}$	c:\guofei\HPHFSS\hpf1086_6

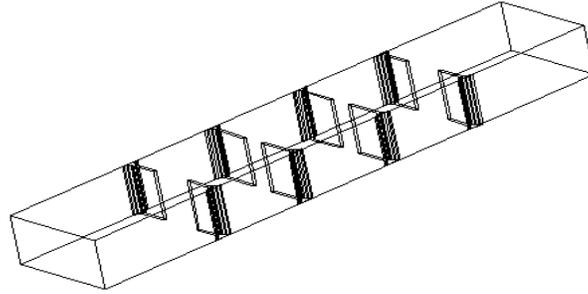


Fig. 1. The 3D geometry of the H-plane resonator filter.

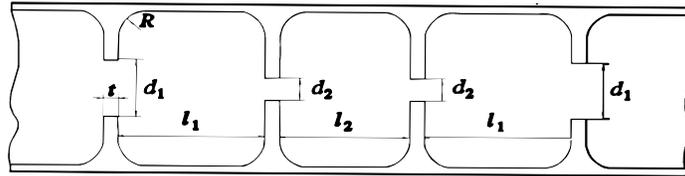


Fig. 2. Top view of the H-plane resonator filter.

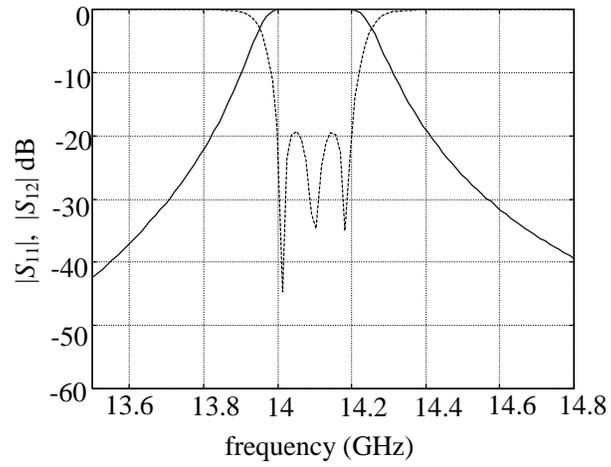


Fig. 3. The optimal coarse model response $|S_{11}|$ dB (---) and $|S_{12}|$ dB (—).

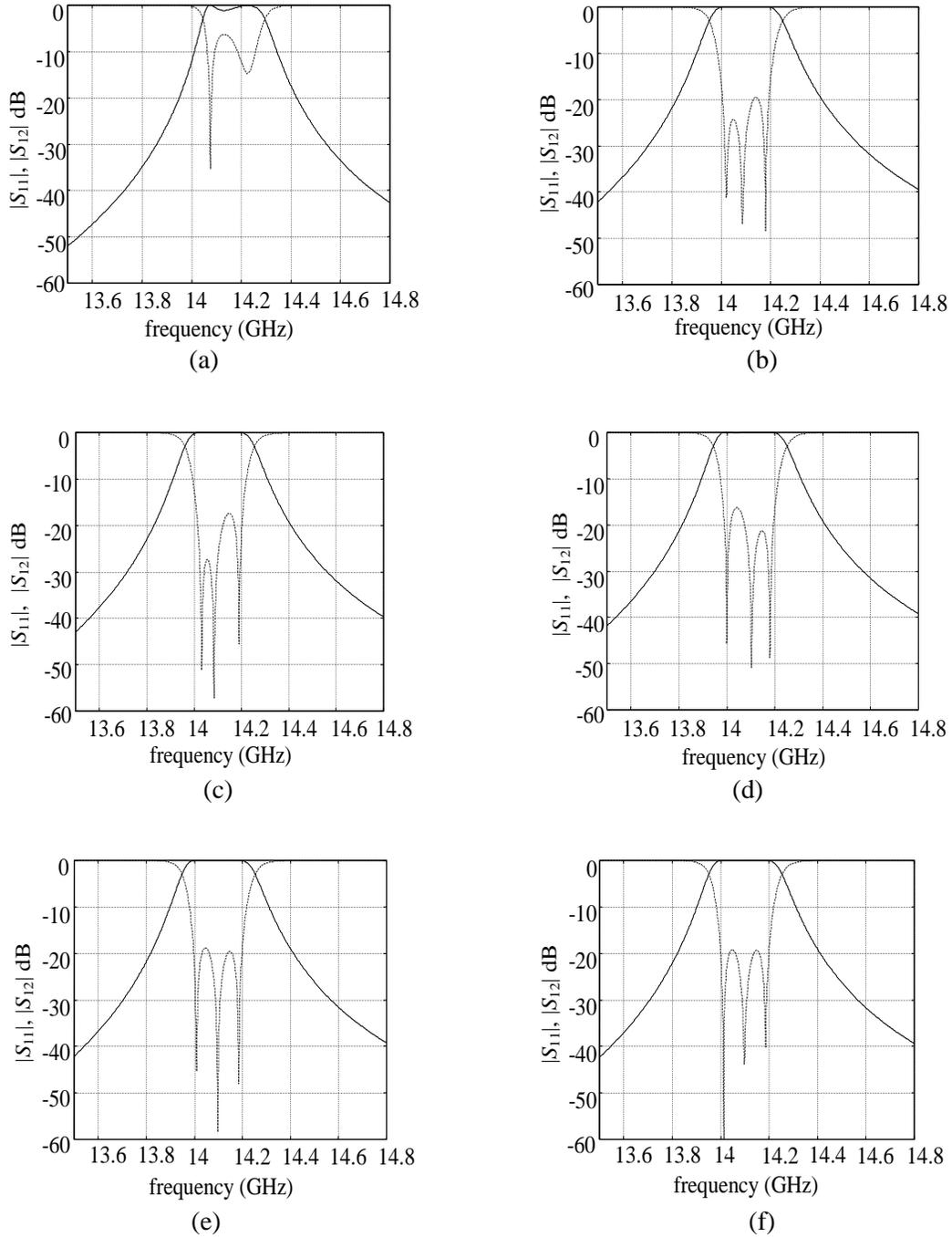


Fig. 4. Results of the fine model simulations in sequence, $|S_{11}|$ dB (---) and $|S_{12}|$ dB (—): (a) the 1st fine model simulation, (b) the 2nd fine model simulation, (c) the 3rd fine model simulation, (d) the 4th fine model simulation, (e) the 5th fine model simulation, (f) the 6th fine model simulation.

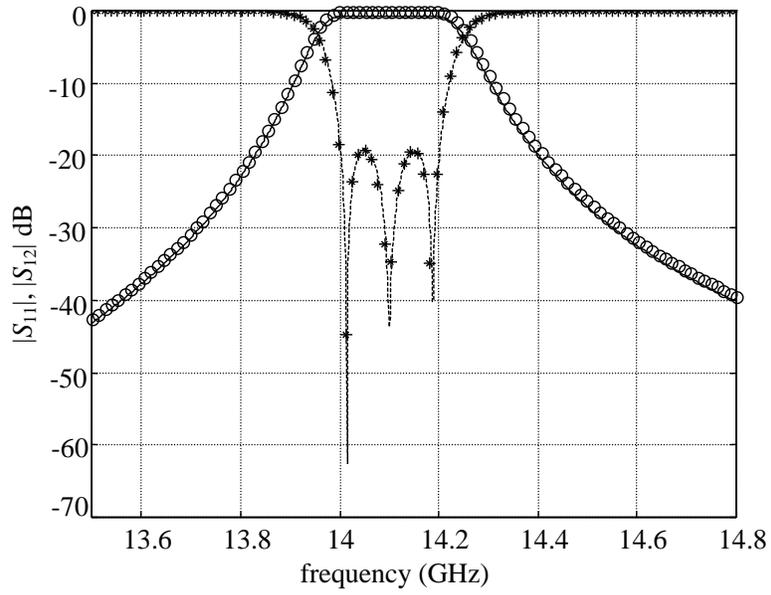


Fig. 5. Comparison of the optimal coarse model response $|S_{11}|$ dB (*) and $|S_{12}|$ dB (o) with the final fine model response $|S_{11}|$ dB (---) and $|S_{12}|$ dB (—).

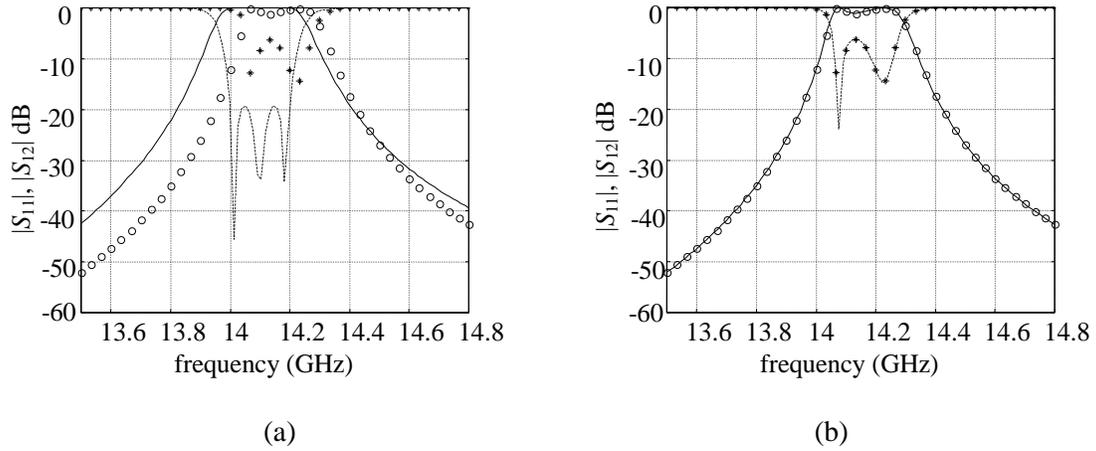


Fig. 6. Comparison of the fine model response $|S_{11}|$ dB (*) and $|S_{12}|$ dB (o) with the coarse model response $|S_{11}|$ dB (---) and $|S_{12}|$ dB (—) before (a) and after (b) parameter extraction at the first step.

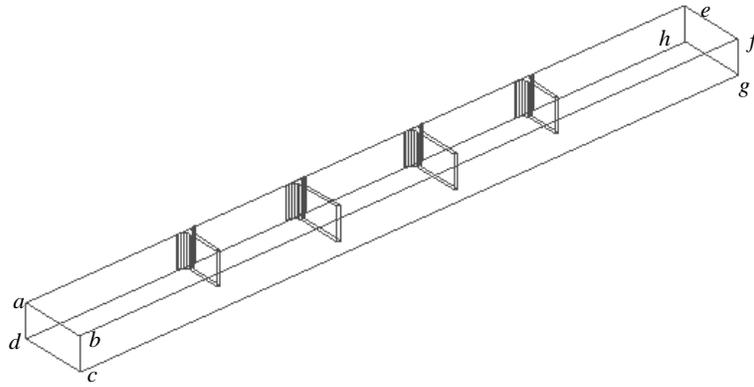


Fig. 7. A quarter of the whole structure used in simulation.

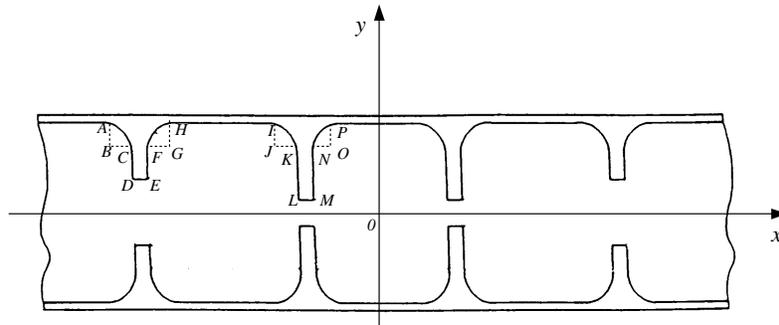


Fig. 8. Determination of the coordinates of some key points.