Time Domain Field Synthesis with 3D Symmetric Condensed Node TLM

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Abstract **– A novel time domain field synthesis approach based on 3D symmetric condensed node TLM will be described. The field distribution on the designable boundary parts is determined through a traditional TLM analysis of a starting geometry. Designable parameters are associated with a set of characteristic frequencies of the structure. The desirable values of these frequencies are determined using design specifications in the form of an equivalent lumped element circuit. A synthesis phase is then carried out for each parameter, during which the associated boundary parts are replaced by matched sinusoidal sources with the desirable value of the associated characteristic frequency. The designable parameter value is determined by observing the envelope of the standing electric/magnetic field pattern.**

I. INTRODUCTION

The traditional design problem of a microwave structure can be formulated as

$$x^* = arg\left\{\begin{matrix} min \\ x \end{matrix}\; U(\boldsymbol{R}(x))\right\} \qquad (1)$$

where x is the vector of designable parameters and $\boldsymbol{R}(x)$ is the vector of responses obtained by electromagnetic simulation. U is the objective function to be minimized and x^* is the vector of optimal designable parameters. U may be selected, if appropriate, as a generalized minmax objective function or L_2 objective function [1].

Classical optimization approaches for solving (1) with a finely discretizing electromagnetic simulator ("fine" model) can be prohibitive. This has motivated research for more efficient optimization approaches. Space Mapping [2], for example, exploits the existence of another fast but less accurate "coarse" model of the circuit under consideration. A bijective mapping is established between the parameter spaces of the electromagnetic and coarse models. This coarse model is then used to guide the optimization iterates, and the final result is mapped back to the "fine" model space. In [3] an analytical expression is derived for the admittance matrix of a finite element analysis of a microstrip circuit. Another approach [4] derives the current derivatives integral equation. The derivatives are then expanded in terms of the same basis functions used in the analysis. The same LU decomposed analysis matrix is reused to solve for the derivatives coefficients. In [5], an adjoint network approach is developed for the FDTD method.

The algorithm suggested in [6] exploits the time reversal property of the Transmission Line Modeling (TLM) method [7]. The TLM impulses corresponding to a desired response are obtained through inverse Fourier Transform. These impulses are then propagated back in time to determine the geometry of the designable discontinuity. This inversion process may not produce a unique result. Also, the absence of higher order modes and high-frequency content in the back-propagated field may reduce the resolution of the discontinuity geometry.

A recent paper describes a novel synthesis technique based on 2D shunt node TLM [8]. The designable parameters are associated with a set of characteristic frequencies of the structure; these frequencies may be resonant frequencies, poles or zeros of responses, etc. The design specifications determine the desired values of these frequencies, most easily in the form of an equivalent lumped element network. A synthesis phase is then carried out for each parameter. In this phase, the corresponding designable boundary parts are replaced by matched sinusoidal sources. The field model is used to determine the new geometry by observing the envelope of the standing electric/magnetic field pattern set up inside the structure.

In this paper, we expand the concept to 3D Symmetric Condensed Node (SCN) TLM. A traditional TLM analysis of a starting geometry is carried out. The relative amplitudes and phases of the 3D TLM impulses representing the tangential electric/magnetic field incident on the designable boundary parts are determined. For each parameter, the desired value of the associated characteristic frequency is then injected.

0-7803-7239-5/02/$10.00 © 2002 IEEE

II. The Synthesis Approach

We extend the time domain synthesis approach suggested in [8] to the 3D TLM case. We begin with the traditional TLM analysis of an initial structure with designable parameters $\boldsymbol{x}_o$. This analysis yields the initial response $\boldsymbol{R}(\boldsymbol{x}_o)$. The approximate field distribution over the designable boundary parts is determined at this stage.

We now associate with each designable parameter a characteristic frequency of the structure. This frequency may be a resonant frequency, a pole, a zero, etc, in other words, a frequency that is mainly determined by that parameter. The associated designable boundary parts are then replaced by matched sinusoidal sources. The frequency of these sources is equal to the desired value of the associated characteristic frequency. We inject the impulses representing the tangential electric/magnetic fields. For the lth boundary link we have

$$V_{li}(k\Delta t) = A_{li}\sin(k\,\omega_d\,\Delta t + \theta_{li}) \qquad (2)$$

where ω_d is the frequency of the injected sinusoidal impulses. A_{li} and θ_{li} are the relative amplitude and phase, respectively, of the lth boundary link and i is the polarization index; i=1, 2. Note that we utilize the same relative amplitude and phase determined in the analysis phase.

The field model finds the minimum energy solution at the injected frequency. The envelope of the standing electric/magnetic field determines the location of electric/magnetic walls and thus the optimal value of the designable parameter.

III. Examples

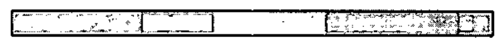
We illustrate our approach through a number of relatively simple examples. The aim is to illustrate the technique rather than to explore its ultimate potential. A commercially available time domain electromagnetic simulator, MEFiSTo [9], is used in all these experiments. The first example shows a 1D transmission line (Fig. 1a) which is short-circuited at the right end. Each subsection of the line has a different permittivity and permeability, indicating that the propagation constant and characteristic may be space-dependent, even dispersive and nonlinear. The task is to place a second short-circuit at a distance L from the first short-circuit such that a 1.0 GHz resonator is created.

Following the traditional optimization procedure we would proceed as follows:

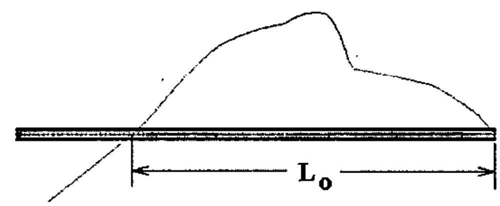
1. Select a starting value L_1 (first guess),
2. Find the resonant frequency f_1 (by experiment, by numerical method, etc). Usually, $f_1 \neq f_0$.
3. Select a new value L_i, and find the corresponding f_i.
4. Find an optimal value L^* that minimizes the difference between its associated f^* and the specified f_0.

This may take several analyses of different resonators; the number depends on the optimization strategy chosen.

Using the proposed synthesis approach, the correct length L_0 can be determined directly by injecting a sinusoidal signal with f_0=1 GHz into the left end of the transmission line. The resulting standing wave pattern (Fig. 1b) yields the exact length L_0 of the resonator in a single experiment or field analysis. Note that the source impedance R_i needs not to be matched to Z_0.



(a)



(b)

Fig. 1 (a) An inhomogeneous section of transmission line, (b) Standing wave pattern at 1.0 GHz obtained with 3D SCN TLM, yielding the length L_0 of a 1.0 GHz resonator in a single synthesis step.

We will now extend this simple 1D case to 2D and 3D structures. We have shown in [8] that wideband S-parameters can be represented by equivalent circuits with lumped elements that we can use to determine a set of characteristic resonant frequencies. We will use that approach in this paper as well.

A. Synthesis of a Rectangular Waveguide Cavity

We consider the design of a simple rectangular TE_{101} cavity for a given resonant frequency of the dominant mode. The cavity has fixed cross-sectional dimensions a=5.7 cm and b=3.3 cm (See Fig. 2). The designable parameter is the cavity length d. The cavity is modeled by a 3D spatial transmission line network. In contrast to the 1D example, the field distribution in the cavity walls is no

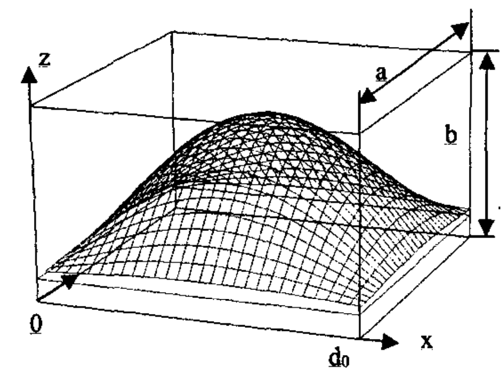


Fig. 2 E_z field distribution in a rectangular cavity resonating in the dominant mode (Analysis phase).

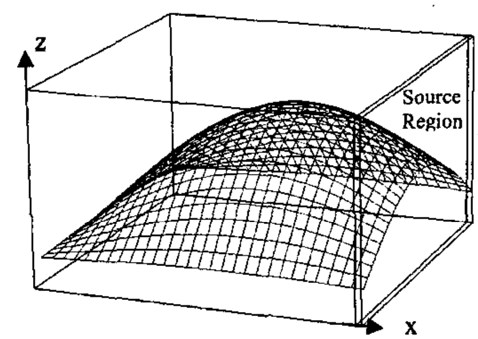


Fig. 3 E_z field distribution due to monochromatic injection at f=0.9 f_0 at x=d_0 (Synthesis phase).

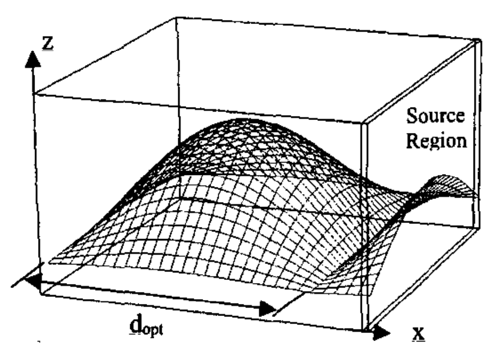


Fig. 4 E_z field distribution due to monochromatic injection at f=1.1 f_0 at x=d_0 (Synthesis phase).

longer uniform but must, in general, be determined by a first guess analysis of a starting structure, unless it is known analytically. We select a starting value d_o=5.7 cm and perform a TLM analysis of the 1st guess structure.

This TLM analysis is carried out by injecting into the cavity a narrow-band Gaussian pulse that contains the dominant mode resonant frequency (which is found to be f_o=3.719 GHz). The relative amplitudes and phases of TLM impulses incident on the right end wall (x=d_0) of the cavity are determined at that resonant frequency. We assume that the thus obtained spatial distribution of the source magnitudes will not change significantly when the length d_0 is changed.

To design the cavity length corresponding to a different resonant frequency, we replace this end wall of the cavity by an array of matched monochromatic TLM sources having the relative amplitudes and phases of the previously recorded incident impulse streams. The frequency of these sources is the desired resonant frequency. Fig. 3 shows the field envelope pattern observed along a horizontal plane for the case f=0.9 f_o, where f is the desired resonant frequency. Clearly, a field null is not obtained within the current length of the cavity. Nevertheless, the field envelope can be extrapolated to zero to determine the new desired cavity length. In this case d_{opt}>d_o. Fig. 4 shows the envelope of the electric field for the case f=1.1 f_o. Here, a clear field null is obtained within the cavity. This null determines the optimal location of the cavity end wall for that resonant frequency, and thus the value d_{opt}. While this cavity can be designed analytically, the example clearly shows the principles and procedures involved.

B. Design of a Ridged Cavity

We now consider the design of a ridged cavity (See Fig. 5). Two inductive ridges of width w=0.7 cm are used to tune the resonant frequency of the cavity. The dimensions of the cavity are a =5.7 cm, b=3.3 cm and d=5.7 cm. The designable parameter is the ridge penetration L. The starting value of this dimension is L_o=0.6 cm. A first analysis of the starting structure with a narrowband excitation containing the first resonant frequency yields f_o=3.877 GHz.

We want to find the ridge penetration that changes the resonant frequency to 6.0 GHz. To this end, the metal face of each ridge is replaced by matched sinusoidal TLM sources (See Fig. 5) with the relative amplitudes and phases recorded during the first analysis. The envelope of the electric field E_z in the window x=$d/2$ between the ridges is observed. Fig. 6 shows that a clear null of the field is obtained. This null determines the optimal length of the ridge. To improve the accuracy, the length obtained is used as a starting value for another round of synthesis iteration. The optimal lengths rounded to the grid are, L_{opt}=2.0 and 2.1cm for ridge-1 and ridge-2, respectively.

Fig. 7 shows the response of the cavity with the synthesized ridge depth obtained by subsequent TLM analysis. Even though the synthesized value is 3.5 times the value of the first guess, only one synthesis step was necessary to obtain the optimal result.

IV. CONCLUSIONS

We have extended field synthesis to the 3D Symmetric Condensed Node (SCN) TLM method. Each designable parameter of a structure is associated with a characteristic frequency. A synthesis phase, which is performed for each designable parameter, determines its optimal value. Our approach has been illustrated through a number of simple examples. More complex structures such as waveguide bandpass filters, are made up of the simpler building blocks described in this paper. The extension to the design of coupled resonators and filters in 3D will be included in the expanded special MTT Transaction issue.

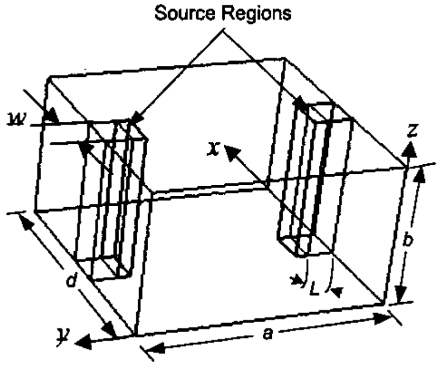


Fig. 5 A ridged cavity with the location of the sources used for the synthesis of the ridge penetration L.

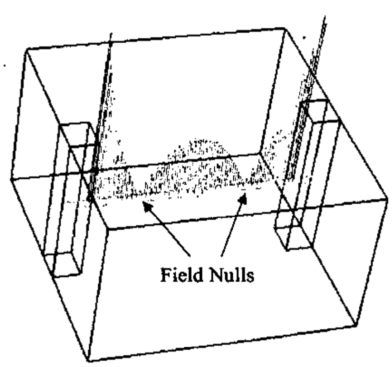


Fig. 6 Envelope of the E_z field pattern produced by an injection of a monochromatic signal at 6 GHz at the ridge faces with L_o=0.6 *cm*.

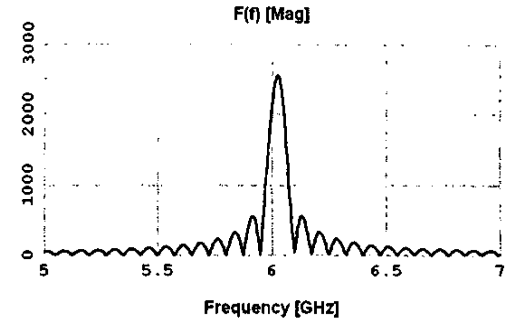


Fig. 7 Response of the cavity with $L=L_{opt}$=2.05 *cm*. Resonant frequency is 6.02 GHz.

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