Researches on Computational Electromagnetics in CEMLAB at UESTC

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Abstract A brief review of the early work, current research areas, and future development of computational electromagnetics in the computational electromagnetics laboratory (CEMLAB) at University of Electronic Science and Technology of China (UESTC) is described. The time-domain and frequency-domain numerical methods are developed to improve simulation efficiency while maintaining the same accuracy for transmission, radiation and scattering problems. The neural network with knowledge-based neurons and generalized transmission line equation techniques are adopted for electromagnetic modeling as CAD tools with high performance. Efficient electromagnetic optimization methods, such as jumping genes genetic algorithm and space mapping technique, are also proposed to optimize antennas and microwave passive components.

Key words frequency domain analysis; genetic algorithm; neural networks; numerical methods; optimization; time domain analysis

电子科技大学计算电磁学实验室对计算电磁学的研究进展

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【摘要】介绍了电子科技大学计算电磁学实验室近年来在计算电磁学领域取得的一些进展和成果。在数值计算方法方面，针对传输、辐射和散射问题，提出了一些新的和改进的时域数值方法和频域数值方法，在保证计算精度的同时提高了仿真的计算效率。在电磁建模方面，提出了知识人工神经网络方法和新型传输线方法，作为高效的CAD工具，其能实现准确和快速的电磁建模。在电磁优化方面，采用跳跃基因遗传算法和空间映射方法对天线和微波无源器件进行了高效率的优化。

关 键 词　频域分析；遗传算法；神经网络；数值方法；优化；时域分析

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Computational electromagnetics (CEM) is an academic discipline combining electromagnetic theory, numerical methods and computer technology. During the past 30 years or so, technical progress of computer and its popularization, evolution of computational mathematics, and requirement of electronic industry, as three stimulating factors, accelerate the CEM researches greatly.

With the improvement and enrichment of numerical techniques, such as the method of moments (MoM), the finite element method (FEM), and finite-difference time-domain (FDTD) method and their variants, significant progress has also been made for electromagnetic (EM) modeling and optimization, e.g., the artificial neural network (ANN) and the genetic algorithm (GA).

In 1993, the computational electromagnetics laboratory (CEMLAB) was founded at UESTC. The researchers concentrated on the FDTD method firstly and then frequency-domain methods, such as finite-difference frequency-domain method and MoM, are also developed in the CEMLAB. At the same time,

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Biography: Wang Bing-zhong was born in 1962. He received the Ph.D. degree in electrical engineering in 1988. He is currently a professor at UESTC. His current research interests include computational electromagnetics, antenna theory and techniques, EMC analysis, and microwave integrated circuits design.

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EM modeling and optimization methods, including general transmission line equations theory, ANN, space mapping technique and GA, are also studied.

This paper summarizes the achievement and progress of the CEMLAB in the research of CEM, including numerical techniques, modeling methods, optimization methods, and so on.

1 Numerical Techniques

1.1 Improved FDTD Method

Because of the accuracy and simplicity, the FDTD method has been widely used for EM simulation, including EM compatibility, scattering, radiation, transmission system, microwave integrate circuit, and so on. However, the stability condition and numerical dispersion, in the FDTD method, are the bottleneck which often results in a long solution time for some complex problems.

1.1.1 Small-Hole Formalism for FDTD Analysis

The modeling of EM coupling into enclosures often requires the resolution of a very small hole. If the hole in an infinitely thin perfectly conducting plate is small with respect to the spatial cell, the spatial cell size must be reduced to that required to resolve the hole. Adequate spatial resolution is often not possible in practical FDTD codes for the heavy computing burden.

Based on the small hole coupling theory of Bethe and the field equivalence theorem, Ref.[1] presents and validates a small-hole formalism (SHF) for the FDTD analysis of small hole coupling. The example shown in Fig.1 is simulated by incorporating the SHF into the traditional FDTD method.

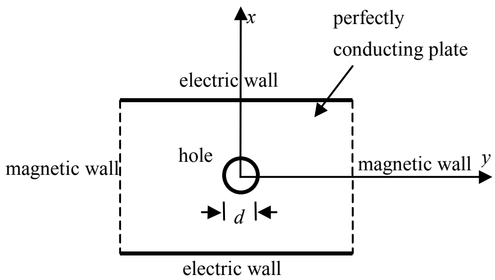


Fig.1 Small circular hole coupling

Fig. 2 shows the waveforms of an electric field component calculated by the SHF. The results by the traditional FDTD algorithm with a much finer resolution of $h/9$ are also shown in Fig. 2. Good agreement has been obtained. The proposed method leads to a large saving of computing time and memory requirement.

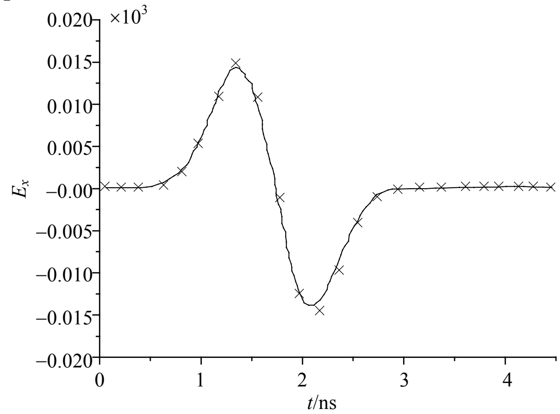


Fig.2 Waveforms of penetrating electric field

1.1.2 Enhanced Slot Formalism for FDTD Analysis

Ref. [2] presents an enhanced thin-slot formalism (ETSF) for the FDTD algorithm, which includes the singularities of field variation near the thin-slot.

Fig. 3 plots a thin slot in a perfect conducting plane. Not from Maxwell's differential equations, Ampere's law and Faraday's law are applied to getting ETSF of the electric and magnetic field components, shown in Fig. 4.

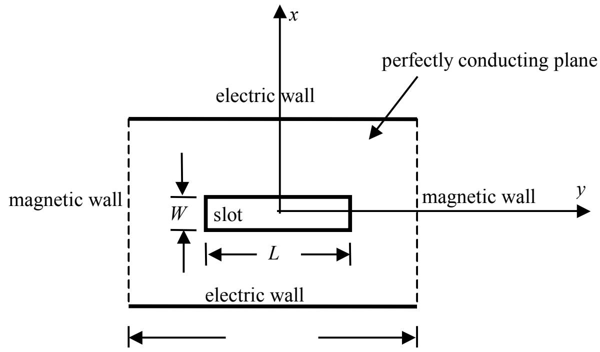


Fig.3 Thin slot in a perfectly conducting plane

W=0.005 m, L=0.06 m

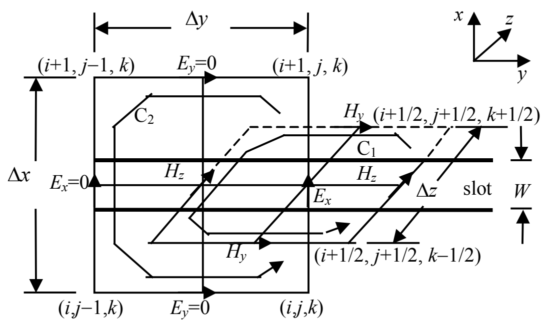


Fig.4 Typical FDTD mesh near the slot

Fig. 5 shows the waveforms calculated by the

ETSF, the standard TSF and the traditional FDTD method respectively, with a much finer resolution of $h/9$. It is obvious that the results given by the ETSF are much better than those by a standard TSF when both of them have the same resolution of h.

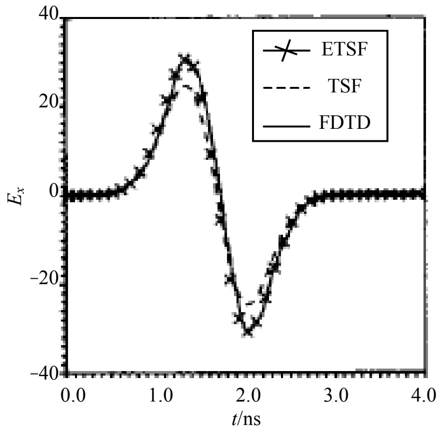


Fig.5 Waveforms of the penetrating electric field

1.1.3 Hybrid ADI-FDTD Subgridding Scheme

A compact 2-D full-wave scheme, based on a combination of the FDTD method and the alternating-direction implicit (ADI) technique, is introduced to extract the propagation characteristics of interconnects [3-5].

Ref.[3] presents a hybrid 2-D full-wave subgridding scheme with unconditionally stable ADI-FDTD method to compute the phase and attenuation constants of the dominant mode of a lossy stripline. The ADI-FDTD scheme is used for fine grid in the vicinity of the metallic etch, while the coarse FDTD grid is used outside this region, shown in Fig. 6. The ADI-FDTD scheme can be synchronized with the time marching step employed in the coarse FDTD scheme, obviating the need for the temporal interpolation of the fields in the process. This helps to render the hybrid ADI-FDTD subgridding scheme to be more efficient than the conventional FDTD subgridding algorithm.

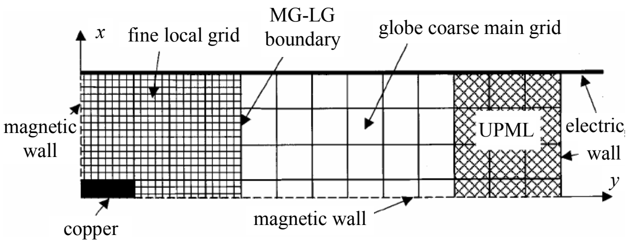


Fig.6 Quarter of the cross section of the lossy stripline

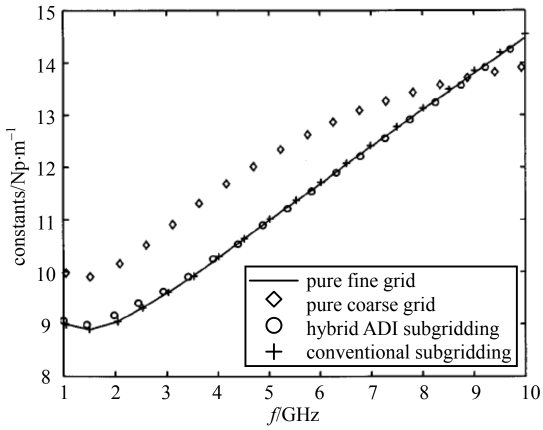


Fig.7 Attenuation constants versus frequency of the lossy stripline calculated with different FDTD schemes

Fig. 7 shows the results for the attenuation constants against frequency. With the exception of the coarse-grid scheme, they are seen to be in good agreement. Although the required memory for the hybrid ADI subgridding scheme is a slightly higher than that of the conventional subgridding scheme because the ADI-FDTD scheme requires more memory for the electrical field components than the FDTD method does, and the run time of the former is only about 60% of that of the latter.

1.2 Space-Domain Finite-Difference Time-Domain Moment Methods

The FDTD method is an explicit time-marching technique, so its stability is tied to cell size through the stability condition and imposes very small time steps in structures involving fine details. This main drawback results in a long solution time for some complex multi-scale problems with fine structures.

We propose a space-domain finite-difference time-domain moment (SDFD-TDM) method based on a combination of finite difference method and moment method. For time-domain Maxwell's differential equations, the new method utilizes Yee's finite-difference scheme in the space domain like the FDTD method. However, it expands time-dependent fields in a series of basis functions like the moment method. It will be proved that the conventional FDTD formulation can be derived from our method by choosing appropriate basis functions and testing functions.

1.2.1　Sub-Domain Triangle Basis Functions

We choose the sub-domain triangle basis functions plus a Galerkin's testing procedure to get an unconditionally stable implicit formulation, which results in a sparse matrix equation [6].

A 2-D parallel plate waveguide with a thin perfect electric conductor (PEC) slot, as shown in Fig. 8, is considered as an example of multi-scale problems. In order to model this thin conductor plate of thickness 4.0 μm, we use the graded mesh, and very small cells are placed around the slot. The PEC slot is divided into two cells, and the minimum cell size is $2.0\ \mu\text{m} \times 0.01\ \text{m}$. The stability condition of this model in the conventional FDTD method is $\Delta t_{\text{FDTD}} < 6.667\ \text{fs}$. In our method, we set $\Delta t = 333.3\ \text{ps}$.

Fig. 9 shows E_y at point p_2. The results of our method are in good agreement with the conventional FDTD method. The CPU time for our method can be reduced to about 3% of the conventional FDTD method while maintaining the same accuracy.

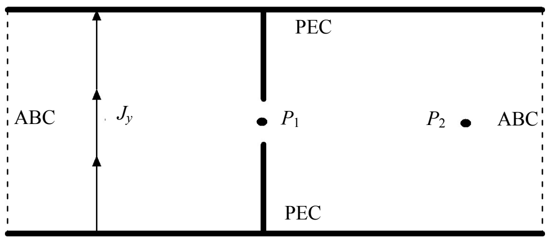


Fig.8　2-D parallel plate waveguide with the thin PEC slot

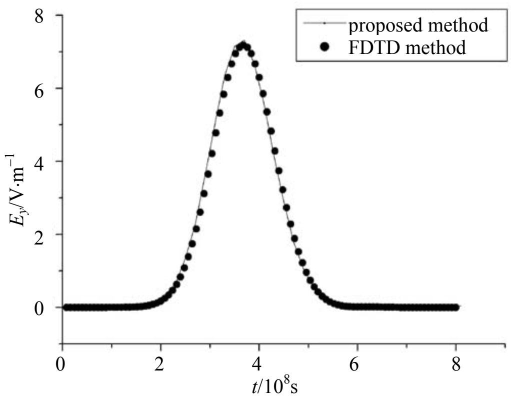


Fig. 9　Transient electric fields of y component at p_2

1.2.2　Entire-Domain Weighted Laguerre Polynomial Basis Functions

Ref.[7] proposes an algorithm based on the compact 2-D FDTD method combined with weighted Laguerre polynomials. Instead of explicit leapfrog time scheme of the conventional compact 2-D FDTD method, the new method chooses weighted Laguerre polynomials as basis functions and Galerkin's method as temporal testing procedure to eliminate the time variable. Thus, an implicit relation, which results in an order-marching scheme, can be obtained. The obtained system matrix is independent of the order. One needs to perform the matrix inversion only once in the computation procedure.

The phase and attenuation constants of a lossy microstrip line shown in Fig. 10 are calculated to validate the proposed method. Fig. 11 shows that the agreement between the results with our method and the results in Ref.[8] is very good. At the same time, stability condition in the compact 2-D FDTD method results in a very small time step and a very long time (at least 10 times of our method) to complete the computation. In our method, the analytical treatment of temporal variables and the separation of temporal and spatial variables lead to an efficient solution.

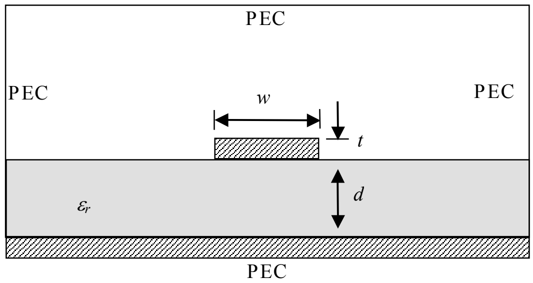


Fig. 10　Cross section of a lossy microstrip line

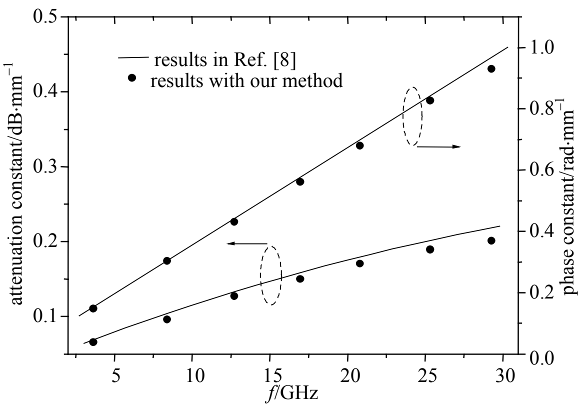


Fig. 11　Phase and attenuation constants for the microstrip line

1.3　Characteristic Basis Function Methods

In characteristic basis function (CBF) methods, the original problem geometry is segmented into smaller regions, and high-level basis functions are generated to represent the EM characteristics of these sections. These basis functions are referred to as the

CBFs, which not only represent the unique EM characteristic of each section, but also include the interactions between different sections, and the parasitic coupling is taken into account in a systematic and efficient manner.

Since the methods only require the solution of small-size matrix equations, associated with isolated domains, the computational burden is relieved, and an acceleration of the solve time is achieved.

1.3.1 Extended Sub-Entire Domain Basis Functions for MoM Method

Refs. [9-10] use an extended accurate sub-entire domain basis functions as CBFs, in which the number of unknowns is further reduced than the original one and the solution time is shorten. For the extended accurate sub-entire domain basis function method, an extended cell including four cells illustrated in Fig. 12 is considered as the support of a single entire-domain basis function. We organize four cells into a cell called an extended cell. A small periodic structure with 36 cells is considered to obtain the CBFs. Thus, the problem with MN_0 unknowns in the conventional MoM is divided into two problems. One includes 36M unknowns. The other involves $N_0/4$ unknowns.

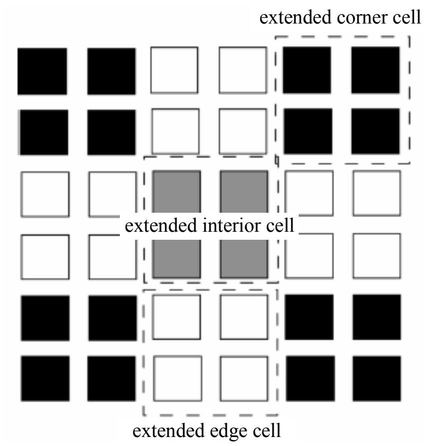


Fig. 12 Periodic structure with all kinds of extended sub-entire domain basis functions

The radar cross sections (RCSs) of an 8×8 array with 0.3λ square plates is calculated. Fig. 13 shows the RCSs of the array when the gap is 0.2λ. It can be observed that our results agree well with those of the MoM and the conventional accurate sub-entire domain (ASED) methods. And our method shows an efficient solution compared with the other method.

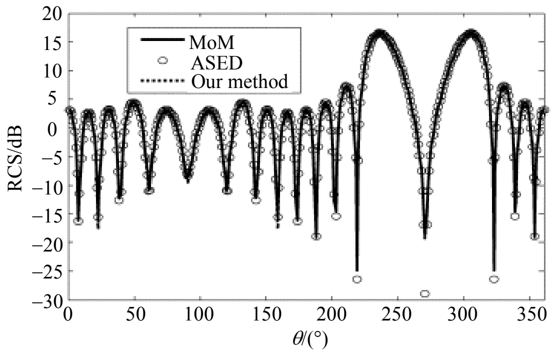


Fig. 13 RCSs of the 8×8 plate array ($\theta = 60°$)

1.3.2 Domain Decomposition Finite-Difference Scheme

Ref.[11] presents an efficient approach for solving a linear system of equations arising in the domain decomposition finite-difference (DDFD) method, which is employed for electrostatic problems. This novel approach is based on utilizing CBFs in which the computational domain is discretized by using the DDFD method. The use of the CBFs leads to a significant reduction in the number of unknowns, and results in a substantial size reduction of the DDFD system; this, in turn, enables us to handle the reduced matrix by using an iteration-free direct solver. The reduced sparse matrix system is solved via the Schur complement approach, which reduces the system into many independent smaller subsystems.

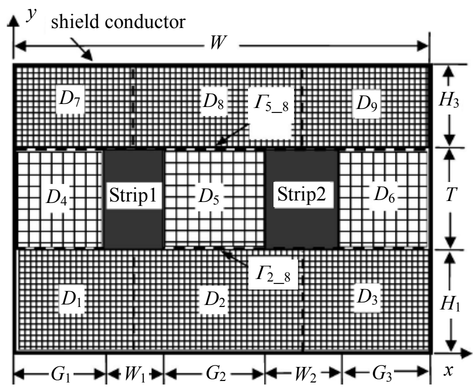


Fig. 14 Shielded coupled stripline and domain decomposition

Using the proposed method, we study a shielded coupled stripline shown in Fig. 14. By solving the corresponding odd- and even-mode problems, each element of the capacitance matrix can be calculated. The results obtained by the proposed approach are shown in Table 1. Our results are in very good agreement with those generated by the direct solver and Schur complement, while the CPU time used by our approach is only about 4% of that required by the direct solver.

Table 1 Comparison for the different method

approach		direct solution	schur complement	CBFM +Schur	relative error/(%)
accuracy	C_{11}/pF·m^{-1}	64.8200	64.820	64.640	−0.3
	C_{12}/pF·m^{-1}	−1.990	−1.990	−2.023	1.7
	C_{22}/pF·m^{-1}	82.510	82.510	82.660	0.2
efficiency	CPU time/s	13.187	3.637	0.578	—
	Ratio/(%)	100.0	27.6	4.4	—

1.4 Meshless Methods

Meshless technique with the FEM is firstly applied to structural mechanics and fluid mechanics. And it models EM owing to its advantages over traditional mesh methods since 1990s.

1.4.1 Radial Basis Functions

Ref. [12] applies the meshless method based on the radial basis functions to solve time-domain Maxwell's equations. The boundary conditions and the current source excitation technique are also discussed. The numerical stability condition of the proposed method is obtained through a one-dimensional (1-D) wave equation and thus the relationship between control parameters is considered.

We use a 1-D EM case with Gaussian pulse excitation to verify the proposed method by comparing the results of the proposed method with that of the FDTD one. Fig. 15 shows that the spatial profiles of the propagation pulse even after oscillation of over 20 periods in PEC boundary condition are still in very good agreement.

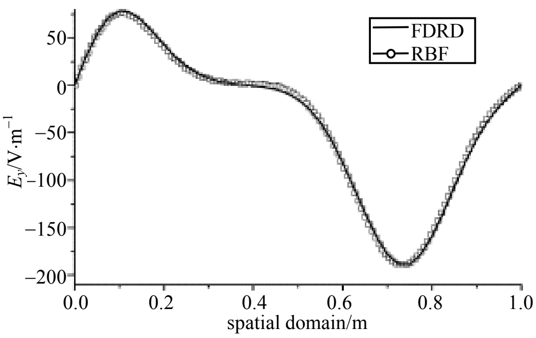


Fig. 15 Comparison of spatial profiles of FDTD and our methods when t =150 ns in PEC boundary condition

The proposed method only relies on a series of random collocation points to discretize the spatial domain, which means not only onerous mesh generation is avoided, but also a more accurate description of irregular complex geometries can be achieved. Furthermore, the meshless approximation, in this example, has higher smoothness, and no additional post-processing is needed.

1.4.2 Element-Free Galerkin Method

The Element-Free Galerkin Method (EFGM) is extended to solve Maxwell's equations of time-domain EM fields[13]. According to the Galerkin based discretization theory, we use a weak form of the governing equations to lower the highest order of derivatives in space domain. Meanwhile, moving least-square (MLS) interpolants has been constructed for the test and trial functions. It costs a little CPU resource because a matrix must be calculated and inverted at every point for every quadrature. However, the high accuracy and good stability can always be obtained. In time domain, the forward difference is used for its stability to construct the time-stepping scheme. The absorbing boundary condition in transient EM is easier to be imposed than essential boundary condition, because the shape function constructed by MLS is not constrained by the Kronecker-condition.

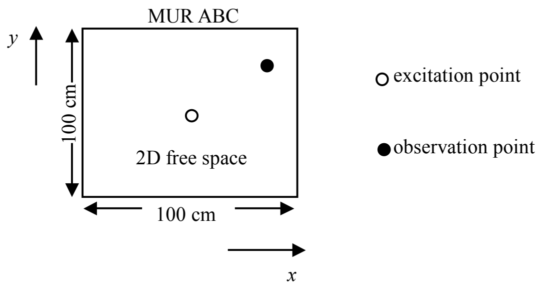


Fig. 16 2-D free-space model

A 2-D free-space model with the Mur's first-order absorbing boundary, plotted in Fig. 16, is taken as the example. The evolution of spatial profiles of H_z component is shown in Fig. 17, in which the results obtained with both FDTD and EFGM simulations are reported for a fixed time-step t=1.19 ns and a fixed spacial slice y=0.5 m. It shows satisfactory agreement between the two numerical computation methods.

The validation of the accuracy and convergency of our method means that it is a promising method in transient EM simulations but without a burdened connectivity law to describe the computational model.

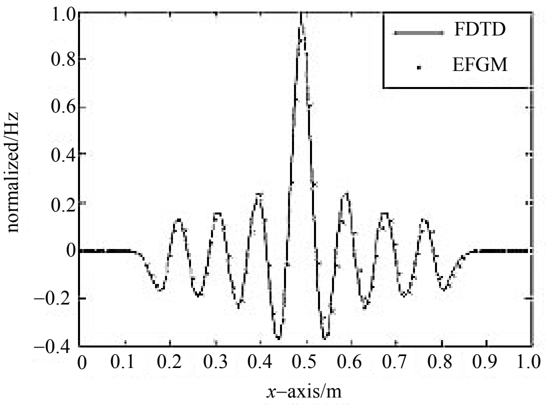


Fig. 17 Spatial profiles of H_z simulated by FDTD and EFGM

2 EM Modeling Techniques

With improved computers, numerical methods, such as the FEM, MoM and FDTD method, are used for accurately solving complex EM problems. However, a small change in the geometrical and material parameters of the structures could result in needing a new time-consuming numerical simulation. The disadvantages of numerical methods prevent their direct application as CAD tools for high performance EM design.

We have been seeking the modeling techniques that can map complex nonlinear input-output relationships at much higher speed than numerical models, yet with the same accuracy as the numerical simulation.

2.1 Neural Network with Knowledge-Based Neurons

We introduce a novel three-layer neural network with knowledge-based neurons (NNKBN), which consists of an input layer, a hidden layer, and an output layer[14-16]. The prior knowledge, in the form of analytical formulae, is used directly to constitute the knowledge-based neurons in the hidden layer. The NNKBN is applied to modeling striplinediscon-tinuities and satisfactory results are obtained.

A training scheme in the NNKBN shown in Fig. 18 is proposed. The training samples are produced by the FDTD simulation of the electrical properties of the stripline discontinuity.

A right angle miter bend of a stripline used in high-speed digital integrate circuits is shown in Fig. 19. For comparison, conventional three-layer multilayer perceptron (MLP) neural network models are also constructed and trained by the same training sample set. The trained NNKBNs and MLP models are then validated using a set of test samples. Fig. 20 shows that the NNKBNs have much better results than those given by the MLP models.

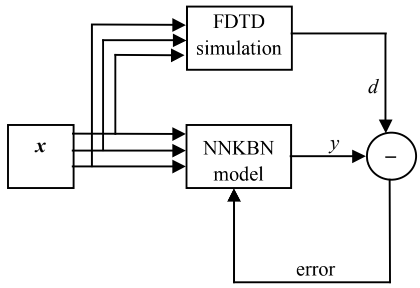


Fig. 18 Training scheme in the NNKBN

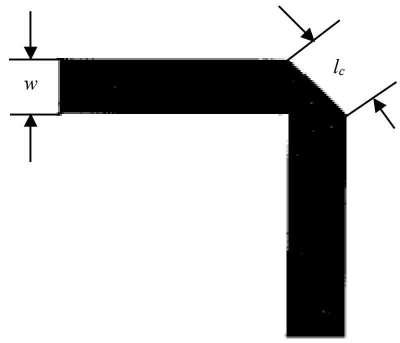


Fig. 19 A right angle miter bend

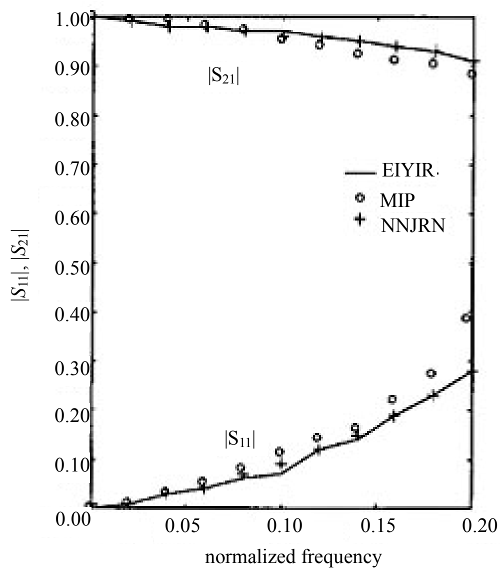


Fig. 20 Comparison of the S-parameters of the bend given by the FDTD simulation, the MLP models and the NNKBNs

2.2 Generalized Transmission Line Equations

In Refs. [17-18], rigorous analysis for a microstrip cross and coplanar waveguide to microstrip (CPW-M) transition is presented by using generalized transmission-line equations. The generalized transmission-line equation is derived from circuit theory, while the equation coefficients are determined from full-wave numerical solutions.

For a microstrip cross shown in Fig. 21, the novel generalized transmission-line equation whose coefficients are determined by MoM can have broadband frequency characteristics. For the investigated microstrip cross, the S parameters for a frequency band from 4 GHz to 24 GHz can be calculated by using only one group of the 2D generalized equation at frequency of 14 GHz. In order to cover the same frequency band obtained by the 2D generalized equations, the MoM has to be repeatedly solved for several times. Since the 2D generalized transmission- line equations are differential equations, while the MoM are the integral equations, the computational speed for solving the 2D differential equations is naturally much faster than that for solving the integral equations. Compared with the conventional nonuniform transmission-line equations, all the transmission-line parameters extracted from the generalized equations are independent of transmission-line excitation and loads.

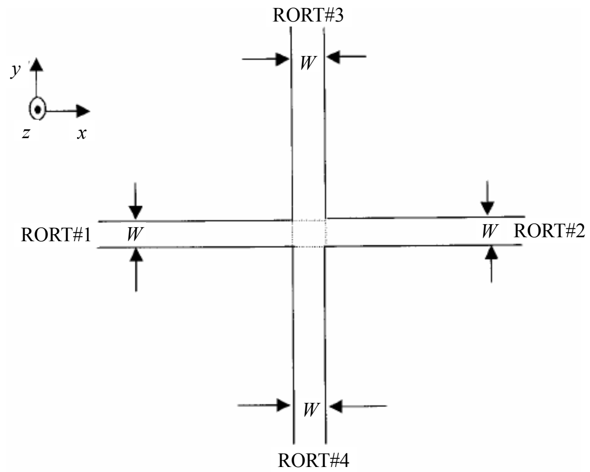


Fig. 21　Geometry of a symmetrical microstrip cross

We use equations obtained at 14 GHz to calculate the S-parameters of the microstrip cross structure for frequency bands of 4 GHz to 24 GHz. A comparison of S_{21} parameters obtained by the equations with the published data and the MoM is shown in Fig. 22 at frequency band of 4 GHz to 24 GHz. Fig. 22 indicates that S_{21} parameters at frequency band of 4 GHz to 24 GHz are all in good agreement, especially for those obtained by the equations and the MoM.

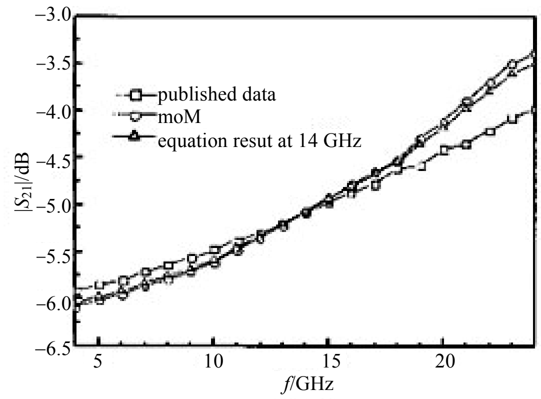


Fig. 22　Comparison of $|S_{21}|$ at 4～24 GHz among the published data, MoM results, and equation results

3　EM Optimization Technique

3.1　Genetic Algorithm

Genetic algorithm (GA) is a robust, stochastic search method modeled on the principles and concepts of natural selection and evolution. As an optimizer, the powerful heuristic of GAs is effective at solving complex, combinatorial and related problems. GA has been proved to be useful for solving complex EM problems. We optimize a new diversity wire antenna configuration with two highly isolated ports using the GA in conjunction with the MOM [19], and apply the GA combined with the FDTD method to the reconfigurable microstrip antennas design [20-21].

Ref.[22] introduces a newly developed GA, called jumping genes multi-objective optimization scheme, to design a planar ultrawideband (UWB) monopole antenna with adjustable dimensions. The jumping genes genetic algorithm (JGGA) has two distinct advantages: (1) it can extend the diversity of non-dominated solutions along the Pareto-optimal front, (2) the non-dominated solutions can converge quickly into the Pareto-optimal front.

The block diagram of the optimization procedure is shown in Fig. 23. In order to obtain a wide impedance bandwidth of a triple-trapezoidal monopole antenna with rectangular ground plane, over the range between 3.1 GHz and 10.6 GHz, a number of parameters are to be optimized, as shown in Fig. 24.

The calculated and measured VSWRs are plotted in Fig. 25. All the results are good and satisfying the design requirements.

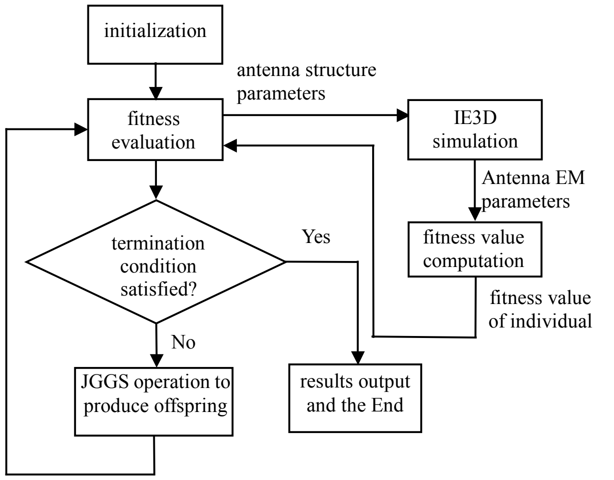


Fig. 23 The block diagram of the optimization

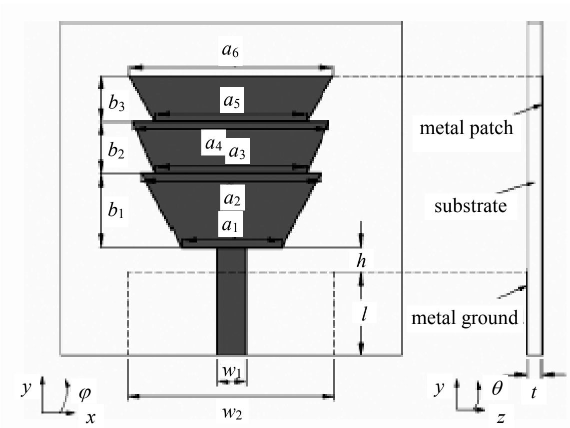


Fig. 24 Configuration of the triple-trapezoidal monopole antenna with rectangular ground plane

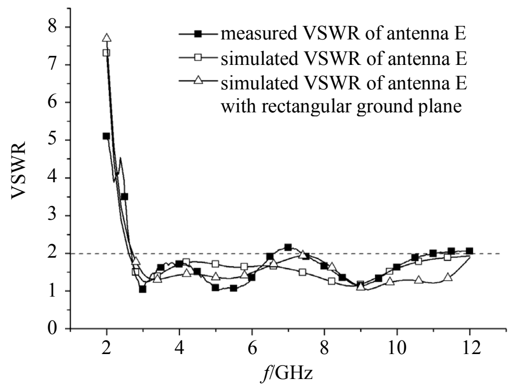


Fig. 25 Measured and simulated VSWRs of the antennas

In this optimization with the JGGA, the final results are obtained only after 27 generations. To confirm, the optimization procedure is carried on till 70 generations, with no better results found. It simply means that the results have converged to the adequate non-dominated solutions merely after 27 generations.

3.2 Space Mapping Technique

The optimization techniques are widely used for device, component, and system modeling. EM simulators, long used for design verification, need to be exploited in the optimization process. However, the higher the accuracy of the simulation, the more expensive direct optimization is expected to be.

The space mapping technique can combine the speed and maturity of circuit simulators with the accuracy of EM solvers. The space mapping intelligently links companion coarse (ideal, fast, or low fidelity) and fine (accurate, practical, or high fidelity) models of different complexities. An EM simulator could serve as a fine model. A low-fidelity EM simulation or empirical circuit model could be a coarse model.

Generally, space mapping optimization algorithms comprise four steps. They are as follows:

(1) Fine model simulation (verification).

(2) Extraction of the parameters of a coarse or surrogate model.

(3) Updating the surrogate.

(4) (Re)optimization of the surrogate.

By using the multiple frequencies space mapping technique, Ref. [23] establishes a parallel capacitor model in low temperature cofired ceramic (LTCC) circuits.

Fig. 26 shows the modeling for multiple frequencies space mapping.

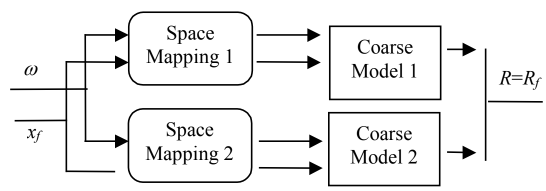


Fig. 26 Multiple frequencies space mapping modeling

A 3-D structure of the four-layer parallel capacitor, which is also the fine model for EM simulation, is plotted in Fig. 27. The geometry parameters in Fig. 27 are to be optimized through the space mapping technique. Fig. 28 shows the corresponding coarse models, which include the Gupta model (less than 6 GHz) and Jansen model (larger than

6 GHz). The two coarse models are used for circuit simulation.

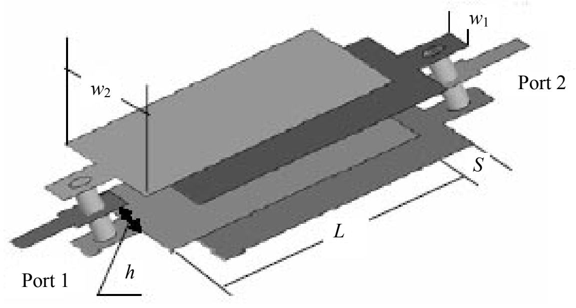
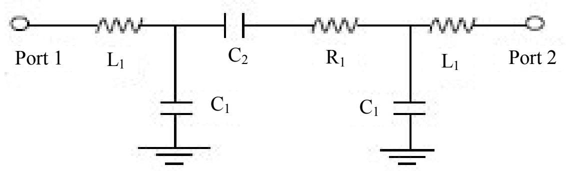
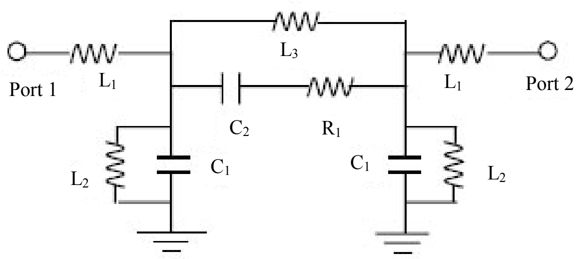


Fig. 27 Fine model of a parallel capacitor

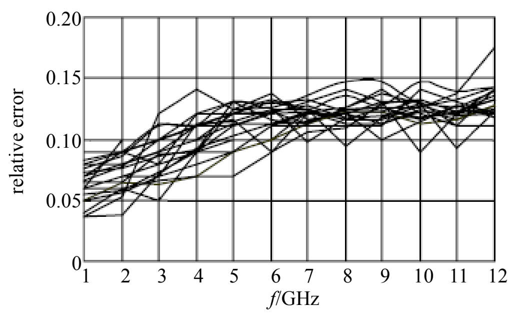


a. Gupta model

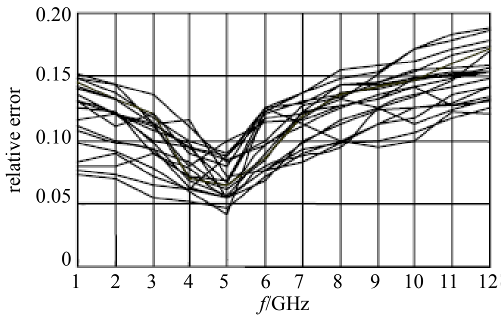


b. Jansen model

Fig. 28 Coarse Models of the capacitor



a. S_{21}



b. S_{11}

Fig. 29 Errors between fine and coarse models

The errors between the fine model and the proposed model, shown in Fig. 29, are acceptable. Notably, the computation time for circuit simulation is further shorter than that for EM simulation, i. e., an efficient optimization for passive components can be obtain by using the space mapping technique.

4 Conclusions

In this paper, we have attempted to provide a short glimpse of some of achievement in the field of CEM obtained in CEMLAB at UESTC. There are still many problems and difficulties that should be solved and investigated. For numerical simulation, the parallel methods, including multi-cores technique and domain-decomposition technique, may be a key to solve the challenging problems. At the same time, the accurate and efficient modeling and optimization methods will be got further studies for EM engineering applications.

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