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PROGRESS REPORT

Title: THREE DIMENSIONAL TRANSIENT ANALYSIS OF MICROSTRIP CIRCUITS IN MULTILAYERED ANISOTROPIC MEDIA

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Under the sponsorship of the ONR contract N00014-90-J-1002, in this period, one paper has been accepted for publication in the *Journal of Electromagnetic Waves and Application*, two papers have been submitted for publication in the Transactions of IEEE, two papers are under preparation, and a chapter has been accepted for publication in the book series *"Progress in Electromagnetics Research"*.

1. The propagation characteristics of signal lines with crossing strips in multilayered anisotropic media

In compact modules of high performance computers, signal transmission lines between integrated circuit chips are embedded in multilayered dielectric medium. These signal lines are usually placed in different layers and run perpendicular to each other. The interaction between the orthogonal crossing lines and the signal line affects its propagation characteristics and may cause considerable signal distortion.

The interaction of a pair of crossing lines in isotropic medium has been studied using a time-domain approach, where coupling is described qualitatively. This method becomes computationally expensive when the number of crossing lines increases. With many identical crossing strips uniformly distributed above the signal line, the transmission properties are characterized by stopbands due to the periodicity of the structure. Periodic structure have been investigated using frequency-domain methods. Periodically nonuniform microstrip lines in an enclosure are analyzed on the basis of a numerical field calculation. A technique based on the network-analytical formulism of electromagnetic fields has been used to analyze striplines and finlines with periodic stubs. The propagation characteristics of waves along a periodic array of parallel signal lines in a multilayered isotropic structure in the presence of a periodically perforated ground plane and that in a mesh-plane environment have been studied. More recently, the effect of the geometrical properties on the propagation characteristics of strip lines with periodic crossing strips embedded in a shielded one-layer isotropic medium have been investigated.

In this work, both open and closed multilayered uniaxially anisotropic structures are considered. A full-wave analysis is used to study the propagation characteristics of a microstrip line in the presence of crossing strips. The signal line and the crossing strips are assumed to be located in two arbitrary layers of a stratified uniaxially anisotropic medium. An integral equation formulation using dyadic Green's functions in the periodically loaded structure is derived. Galerkin's method is then used to obtain the eigenvalue equation for the propagation constant. The effects of anisotropy on the stopband properties are investigated. Numerical results for open and shielded three-layer uniaxially anisotropic media are presented.

2. Finite-difference time-domain method for single and coupled microstrip lines

The Finite-Difference Time-Domain (FD-TD) method was first introduced by Yee who discretized Maxwell's time dependent curl equations with second-order accurate central-difference approximations in both the space and time derivatives. Since then, it has been applied extensively to scattering and wave absorption problems. Application of the FD TD method to microstrip problems, in which frequency-domain approaches have dominated, has so far attracted little attention.

The finite-difference method in the time domain has been applied to the solution of three-dimensional eigenvalue problems, where the resonant frequencies of fin lines have been obtained. The dispersion characteristics of an open microstrip line have been obtained using the FD-TD method where the open-circuit, short circuit absorbing boundary conditions have been applied to simulate the unbounded space. Fourier transform of the transient results has been used to obtain the frequency dependent effective dielectric constant and the characteristic impedance. FD-TD is further extended to the analyses of open microstrip discontinuities on isotropic substrates where the scattering parameters for microstrip open-end, cross junction, T-junction, step-in-width, and gap are presented.

In this work the FD-TD algorithm for microstrip problems in isotropic media together with boundary treatments are described. For proper simulation of a matched source, the magnetic wall source plane (MWSP) and the symmetric wall source plane (SWSP) are proposed to obtain more accurate frequency domain results. The modeling of conducting strips in the numerical grid is investigated. It is shown that with proper treatment of the strip edge, accurate results can be obtained even with course grid and thus much reduction in computation time is achieved. Numerical results for single and coupled microstrip lines using the MWSP and the SWSP treatments are presented and compared with those obtained form the full-wave frequency domain method using dyadic Green's function approach.

3. Modelling of lossy microstrip lines with finite thickness

For microwave integrated circuit applications, the characteristics of interconnects have been investigated for the propagation modes, time response, crosstalk, coupling, delay, etc. In these analyses, it is assumed that quasi-TEM modes are guided along the multiconductor transmission lines. The analysis were performed for arbitrary number of transmission lines where the load and the source conditions were presented in terms of the modal reflection and transmission coefficient matrices.

To perform the quasi-TEM analysis, the capacitance matrix for the multiconductor transmission line has to be obtained first. Both the spectral and the spatial domain methods have been proposed to calculate the capacitance matrix. In the spectral domain methods, two side walls are used to enclose the whole transmission line structure, and the thickness of the strip lines has not been considered. In using the spatial domain method, the structure has to be truncated to a finite extent to make the numerical implementation feasible. The infinite extent of the structure was also incorporated, but only a two-layer medium was considered.

In practical microwave integrated circuits, the dielectric loss due to the substrate and the conductor loss due to the metallic strips are also studied in the analysis of circuit performances.

In this work we present a quasi-TEM analysis for multiconductor transmission lines with finite strip thickness embedded in arbitrary layers of a lossy isotropic stratified medium. A spectral domain scalar Green's function of a uniform line charge immersed in a lossy isotropic stratified medium is introduced. In the formulation, no side walls are introduced, the transmission structure is not truncated, and the analysis is valid for arbitrary number of dielectric layers.

Based on the scalar Green's function, a set of coupled integral equations is obtained for the charge distribution on the strip surfaces. Pulse basis functions and a point-matching scheme is used to solve numerically the set of integral equations for the charge distribution, and hence the capacitance matrix. The duality between the electrostatic formulation and the magnetostatic one is applied to calculate the inductance matrix. The conductance matrix is obtained by using the duality between the electrostatic problem and the current field problem. A perturbation method is used to calculate the resistance matrix.

Finally, a transmission line analysis is derived to obtain the transfer matrix for multiconductor uniform lines, which significantly reduces the effort in treating the load and the source conditions. Transient responses are obtained by using the Fourier transform. The results for two coupled lines are presented.

4. A hybrid method for the calculation of resistance and inductance of transmission lines with arbitrary cross section

With the ever increasing speed and density of modern integrated circuits, the need for electromagnetic wave analysis of phenomena such as the propagation of transient signals, especially the distortion of signal pulses, becomes crucial. One of the most important causes of pulse distortion is the frequency dependence of conductor loss, which is caused by the "skin effect", and which can be incorporated into the circuit models for transmission lines as frequency-dependent resistance and inductance per unit length. Efficient and accurate algorithms for calculating these parameters are increasingly important.

In this work, a new, hybrid cross-section finite element/coupled integral equation method is presented, which is both efficient and flexible in regards to the kinds of configurations which can be handled. The technique is a combination of a cross-section finite element method, which is best for high frequencies. An interpolation between the results of these two methods gives very good results over the entire frequency range, even when few basis functions are used.

For low frequencies, we use a cross-section finite element method. Our method is based on the Weeks method, but with two major modifications. First, we use triangular patches, rather than the rectangular patched used by Weeks; secondly, we do not change the distribution of patches with frequency. It is shown that both of these improvements, along with the fact that we do not use the cross-section method for high frequencies, greatly increase the efficiency of the method.

In the cross-section method, we divide each conductor into triangular patches and choose one of the patches from the return conductor to be our reference. We then calculate the resistance and inductance matrices for the patches. Using two conditions on the system, that the total current in each wire is the sum of the currents in the patches, and that the voltage on each patch in a wire must be the same (no transverse currents), we can reduce the matrices for the patches to the matrices for the wires. In the Weeks method, the patches are rectangles, and the quadruple integral is done quite easily in closed form. However, it is also possible to evaluate the quadruple integral in closed form for triangular patches, although the mathematics leading to this result is quite involved, and the final form of the answer is complicated. We therefore use triangular patches as the most flexible means of modelling conductors with arbitrary cross-sections; polygons are covered exactly, and we are able to model quite closely other shapes, such as circles.

As frequency increases, the need to keep the uniform current approximation valid in the patches requires either the addition of many more patches as the skin depth decreases, or a redistribution of the existing patches to the surface, where the current is. However, changing the distribution of patches makes it necessary to recalculate the resistance and inductance matrices of the patches, thus increasing the computation time. Since we use a surface integral equation method for high frequencies, we do not change the distribution of the triangular patches for the cross-section method as we increase the frequency.

For high frequencies, we use a coupled surface integral equation technique. Under the quasi-TEM assumption, the frequency-dependent resistance and inductance result from the power dissipation and magnetic stored energy, which can be calculated by solving a magnetoquasistatic problem, with the vector potential satisfying Laplace's equation in the region outside all the conductors. The resistance and inductance are usually given by integrals of these field quantities over the cross-sections of the wires, but by using some vector identities it is possible to convert these expressions to integrals only over the surfaces of the wires. These expressions contain only the current at the surface of each conductor, the derivative of that current normal to the surface, and constants of the vector potential.

A coupled integral equation is then derived to relate these quantities through Laplace's equation and its Green's function outside the conductors and the diffusion equation and its Green's function inside the conductors. The method of moments with pulse basis functions is used to solve the integral equations. This method differs from previous work in that the calculation of resistance and inductance is based on power dissipation and stored magnetic energy, rather than on impedance ratios. It will therefore be more easily extended to structures where non-TEM propagation can occur.

For the intermediate frequency range, where the conductors are on the order of the skin depth, were found it very efficient to interpolate between the results of the cross-section and surface methods. The interpolation function was based on the average size of the conductors, measured in skin depths, and was of the form $1/(1+0.16a^2/\delta^4)$, where it a is the average cross-section of the conductors, and δ is the skin depth.

5. Analysis of frequency-dependent complex systems with nonlinear terminations

Most of microwave and digital integrated circuits are terminated with semiconductor devices, such as diodes and transistors, having nonlinear input impedances. With sufficient high magnitude of signals the terminal loading condition of the circuit will vary with the amplitude of transmitted signals. The nonlinear effects of the terminal load should then be taken into account. Two commonly-used methods to deal with this kind of nonlinear problems are the direct time domain approach and the combination of time domain treatment with frequency analysis, such as the harmonic balance and the modified harmonic balance techniques.

As the speeds of integrated circuits and the operating frequency range of microwave circuits increase, the frequency-dependent effects can no longer be neglected. In this case, the problem becomes more complicated, and the approaches mentioned above cannot be readily applied. The direct time domain approach is inapplicable to frequency-dependent systems. The harmonic balance and modified harmonic balance techniques have the common deficiency that they are inefficient in treating a nonlinear system supporting signals having very wide frequency bandwidths, such as narrow pulses of less than one nanosecond in duration.

A nonlinear analysis in the time domain using impulse responses from a frequency domain analysis based on the admittance matrix was presented. The principle of this method is to first obtain the impulse responses through analyzing the linear portion of the investigated system in the frequency domain, and then using the impulse responses to solve the entire nonlinear problem in the time domain. This method has been improved through artificially introducing quasi-matched passive networks. This method can be applied to nonlinearly-loaded frequency dependent transmission line problems. Modified approaches have been developed by using the concept of wave transmission and reflection instead of voltage and current. These modified methods overcome the necessity of using artificial quasi-matched networks. However, only a single transmission line or a two port system has been discussed.

In this work, a generalization of the modified method is presented to analyze arbitrary multi-port systems containing frequency dependent elements as filters, discontinuities, and loads containing nonlinear resistances and capacitances. The method is applied to analyze a pair of coupled dispersive transmission lines partly terminated in nonlinear load, and discontinuity effects of uncompensated and compensated right angle microstrip corners. Finally, the transient response of a microwave switcher is presented.

6. Input impedance of a probe-fed stacked circular microstrip antenna

Conventional microstrip antennas, consisting of a single perfectly conducting patch on a grounded dielectric substrate, have received much attention in recent years due to their many advantages, including low profile, light weight, and easy integration with printed circuits. However, due to their resonant behavior their use is severely limited in that they radiate efficiently only over a narrow band of frequencies, with bandwidths typically only a few percent. While maintaining the advantages of conventional single patch microstrip antennas, microstrip antennas of stacked configurations, consisting of one or more conducting patches parasitically coupled to a driven patch, overcome the inherent narrow bandwidth limitation by introducing additional resonances in the frequency range of operation, achieving bandwidths up to 10-20 percent. In addition, stacked microstrip configurations have achieved higher gains and offer dual frequency operation.

The first multilayered microstrip element was described by Oltman as an electromagnetically coupled microstrip dipole where a printed dipole was excited by an open-ended microstrip transmission line in the same plane as the dipole or in the layer below the dipole. Hall et al. stacked rectangular microstrip patches in two- and three-layer configurations, achieving bandwidths in excess of 16 times that of alumina substrate microstrip antennas, and noted that the stacked configurations allowed for simple antenna/circuit integration. Experimental work by others with two-layer stacked circular and rectangular microstrip patches produced wider bandwidths and higher efficiencies than those obtained with conventional single patch configurations. Stacking microstrip patches for dual frequency use was investigated experimentally for circular disks by Long et al. and for annular rings by Dahele et al.

While the experimental work has been abundant, the theoretical work is limited. The open structure of the stacked microstrip antenna configuration has been analyzed to study the resonant frequencies, modes, and radiation patterns. Using the Hankel transform, a numerical analysis of a circular microstrip disk antenna with a parasitic element is presented. The resonant frequencies of the stacked microstrip disks have been rigorously calculated and related to the constitutive resonances of the stacked configuration. The method of moments with triangular basis functions was employed to analyze the open structure of a two-layer circular microstrip antenna excited by an incident plane wave. A spectral domain iterative analysis of single- and double-layered microstrip antennas using the conjugate gradient algorithm to compute radiation patterns was described. In particular, to the knowledge of the authors', there is little or no theoretical analysis of the input impedance of coaxial probe-fed stacked microstrip patches. However, the input impedance for conventional single-layer coaxial probe-fed microstrip antennas of circular, rectangular, annular ring, and elliptic geometries has been investigated by many authors. The impedance parameters of two planar coupled microstrip patches have also been studied.

In the calculation of the input impedance of probe driven microstrip antennas on thin substrates, the effect of the probe results in an additional inductive component to the input impedance. This probe inductance has been accounted for by several authors through use of a simple formula. In more rigorous methods to include the effects of the probe, an "attachment mode" in the disk current expansion is used to account for the singular behavior of the disk current in the vicinity of the probe, ensure continuity of the current at the probe/disk junction, and speed up the convergence of the solution. An "attachment mode" which represented the disk current of a lossy magnetic cavity driven by a uniform cylindrical probe current was introduced. More recently, a similar "attachment mode" has been applied. Other "attachment modes," with the $1/\rho$ dependence in the vicinity of the probe and the appropriate boundary condition on normal current, defined over the entire disk or locally over a portion of the disk, have also been used. The problem of center-fed microstrip disk was investigated including both "attachment mode" and edge current terms. In a different approach, the effects of the probe were accounted for by expanding the currents on the disk and probe in terms of the modes of a cylindrical magnetic cavity satisfying boundary conditions on the eccentrically located probe. Radiation losses were accounted for by an effective loss tangent and fringing fields by an effective disk radius.

Considered here is a microstrip antenna consisting of two circular microstrip disks in a stacked configuration driven by coaxial probe excitation. The two different stacked configurations are investigated. A rigorous analysis of the two stacked circular disks in a layered medium is performed using a dyadic Green's function formulation. Using the vector Hankel transform, the mixed boundary value problem is reduced to a set of coupled vector integral equations and solved by employing Galerkin's method in the spectral domain. The current distribution on each disk is expanded in terms of two sets of basis functions. The first set of basis functions used are the complete set of transverse magnetic (TM) and transverse electric (TE) modes of a cylindrical resonant cavity with magnetic side walls. The second set of basis functions used employ Chebyshev polynomials and enforce the current edge condition. An additional term in the current expansion is taken to account for the singular nature of the current on the disk in the vicinity of the probe and to ensure continuity of current at the junction. This term, the "attachment mode," is taken to be the disk current of magnetic cavity under a uniform cylindrical current excitation. It is shown here explicitly that continuity of the current at the probe/disk junction must be enforced to rigorously include the probe self-impedance. The convergence of the results is investigated and ensured by using a proper number of basis functions. The input impedance of the stacked microstrip antenna is calculated for different configurations of substrate parameters and disk radii. Disk current distributions and radiation patterns are also presented. Finally, the results are compared with experimental data and shown to be in good agreement.

7. Radiation from VLSI package configurations

There is a common perception that stripline configurations will generate lower emissions levels than microstrip structures. Supporting this perception necessitates an evaluation of the effect of the finite-size reference planes constituting the stripline structures. The finite dimensions allow energy leakage from the edges. The problem may be compounded by the existence of stub-like plating bars in chip packages or discontinuities in the vicinity of the plane edges.

Using the finite-difference time-domain method, the problem of radiation of stripline with truncated ground planes is under investigation. The radiation properties of discontinuities placed on both truncated microstrip and stripline environment will be studied.

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The propagation characteristics of signal lines with crossing strips in multilayered anisotropic media (C. M. Lam, S. M. Ali, and J. A. Kong), *Journal of Electromagnetic Waves and Application*, Vol. 4, No. 10, 1005–1021, 1990.

Finite-difference time-domain method for single and coupled microstrip lines (C. W. Lam, S. M. Ali and J. A. Kong), *IEEE Transactions on Microwave Theory and Techniques*, submitted for publication.

Modelling of lossy microstrip lines with finite thickness (J. F. Kiang, S. M. Ali and J. A. Kong), *Progress in Electromagnetics Research*, Elsevier Publishing Company.

A hybrid method for the calculation of resistance and inductance of transmission lines with arbitrary cross section (M. J. Tsuk and J. A. Kong), *IEEE Transactions on Microwave Theory and Techniques,* submitted for publication.

Analysis of frequency-dependent complex systems with nonlinear terminations (Q. Gu. and J. A. Kong), *IEEE Transactions on Microwave Theory and Techniques,* submitted for publication.

Input impedance of a probe-fed stacked circular microstrip antenna (A. Tulintseff and J. A. Kong) *IEEE Transactions on Antennas and Propagation*, accepted for publication.

Radiation from VLSI Package Configurations (C. W. Lam, S. M. Ali, and J. A. Kong), under preparation.

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