UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

DTIC FILE COPY (2)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

AD-A229 746

- **1a. REPORT SECURITY CLASSIFICATION:** Unclassified
- **1b. RESTRICTIVE MARKINGS:**
- **3. DISTRIBUTION/AVAILABILITY OF REPORT:** Approved for public release; distribution unlimited.
- **5. MONITORING ORGANIZATION REPORT NUMBER(S):**
- **6a. NAME OF PERFORMING ORGANIZATION:** Research Laboratory of Electronics, Massachusetts Institute of Technology
- **6b. OFFICE SYMBOL (If applicable):**
- **6c. ADDRESS (City, State, and ZIP Code):** 77 Massachusetts Avenue, Cambridge, MA 02139
- **7a. NAME OF MONITORING ORGANIZATION:**
- **7b. ADDRESS (City, State, and ZIP Code):**
- **8a. NAME OF FUNDING/SPONSORING ORGANIZATION:** Office of Naval Research
- **8b. OFFICE SYMBOL (If applicable):**
- **8c. ADDRESS (City, State, and ZIP Code):** 800 North Quincy St., Arlington, VA 22217
- **9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:** N00014-89-J-1019
- **10. SOURCE OF FUNDING NUMBERS:**

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
	4143115-02		

- **11. TITLE (Include Security Classification):** Theoretical Analysis of Microwave and Millimeter Wave Integrated Circuits...
- **12. PERSONAL AUTHOR(S):** Prof. J.A. Kong
- **13a. TYPE OF REPORT:** Annual Technical
- **13b. TIME COVERED:** FROM 10-1-89 TO 09-30-90
- **14. DATE OF REPORT (Year, Month, Day):** November 1990
- **15. PAGE COUNT:** 20
- **16. SUPPLEMENTARY NOTATION:**

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

- **18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number):**
- **19. ABSTRACT (Continue on reverse if necessary and identify by block number):**

Work by Prof. J.A. Kong and his collaborators is summarized here. Keywords: Microwave equipment, Integrated circuits, microwaves. (RH)

DTIC ELECTE DEC 06 1990 S E D

- **20. DISTRIBUTION/AVAILABILITY OF ABSTRACT:** ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS
- **21. ABSTRACT SECURITY CLASSIFICATION:** Unclassified
- **22a. NAME OF RESPONSIBLE INDIVIDUAL:** Mary Greene - RLE Contract Reports
- **22b. TELEPHONE (Include Area Code):** (617)258-5871
- **22c. OFFICE SYMBOL:**

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

PROGRESS REPORT

Title: THEORETICAL ANALYSIS OF MICROWAVE AND MILLIMETER WAVE INTEGRATED CIRCUITS BASED ON MAGNETIC FILMS

Sponsor by: Department of the Navy
Office of Naval Research

Contract number: N00014-89-J-1019

Research Organization: Center for Electromagnetic Theory and Applications
Research Laboratory of Electronics
Massachusetts Institute of Technology

OSP number: 71387

Principal Investigator: J. A. Kong

Author of Report: S. M. Ali

Period covered: October 1, 1989 — September 30, 1990

Scientific Personnel Supported by this Project:

Jin Au Kong:	Principal Investigator
Sami M. Ali:	Research Scientist
Ann N. Tulintseff:	Graduate Student
Michael J. Tsuk:	Graduate Student
Qizheng Gu:	Visiting Scientist
David M. Sheen:	Graduate Student
Chang W. Lam:	Graduate Student
Jiquing Xia:	Graduate Student

Accession For
NTIS GRA&I ☒
DTIC TAB ☐
Unannounced ☐
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or Special
A-1

90

THEORETICAL ANALYSIS OF MICROWAVE AND MILLIMETER WAVE INTEGRATED CIRCUITS BASED ON MAGNETIC FILMS

Under the sponsorship of the ONR Contract Contract N00014–89–J-1019 we have published 26 referenced journal and conference papers.

We present an inversion algorithm based on a recently developed inversion method referred to as the Renormalized Source-Type Integral Equation approach. The objective of this method is to overcome some of the limitations and difficulties of the iterative Born technique. It recasts the inversion, which is nonlinear in nature, in terms of the solution of a set of linear equations; however, the final inversion equation is still nonlinear. The derived inversion equation is an exact equation which sums up the iterative Neuman (or Born) series in a closed form and; thus, is a valid representation even in the case when the Born series diverges; hence, the name *Renormalized* Source-Type Integral Equation Approach.

The coupled-wave theory is generalized to analyze the diffraction of waves by chiral gratings for arbitrary angle of incidence and polarizations. Numerical results are illustrated for the Stokes parameters of diffracted Floquet modes versus the thickness of chiral gratings with various chiralities. Both horizontal and vertical incidences are considered for illustration. The diffracted waves from chiral gratings are in general elliptically polarized; and at some particular instances, it is possible for chiral gratings to convert a linearly polarized incident field into two nearly circularly polarized Floquet modes propagating in different directions.

The scattering and receiving characteristics of a probe-fed stacked circular microstrip antenna, both as an isolated element and in an infinite array, are investigated.

The receiving case, where the antenna is loaded with impedance Z_L, is solved by superposition, decomposing the problem into the scattering case with $Z_L = 0$ and the transmitting case. In the scattering case, the coaxial probe is short-circuited to the ground plane and the induced probe current I_1 due to an incident plane wave excitation is determined. In the transmitting case, a voltage V is applied to the base of the probe and the input impedance Z_{in} is solved for, giving a relationship between the applied voltage V and the transmitting probe current I_2. With the knowledge of I_1 and Z_{in}, for a given load impedance Z_L, the total probe current, $I = I_1 + I_2$, and the received power are determined.

The scattering and transmitting problems are solved rigorously using a dyadic Green's function formulation where the mixed boundary value problem is reduced to a set of coupled vector integral equations for the unknown disk and probe currents. Galerkin's method is employed in the spectral domain where the disk current distributions are expanded in terms of the complete set of transverse magnetic (TM) and transverse electric (TE) modes of a cylindrical resonant cavity with magnetic side walls. An additional term is added to the disk current expansion to properly model the singular behavior of the current in the vicinity of the probe, to ensure continuity of the current at the probe/disk junction, and to speed up the convergence of the solution.

The radar cross section (RCS) of a single stacked microstrip antenna is calculated for both the open and short-circuited cases. For an infinite array of phased elements, the reflection coefficient seen at the input of the antenna and the received power are calculated.

The complex resonant frequencies of the open structure of a microstrip antenna consisting of two circular microstrip disks in a three layer stacked configuration have been rigorously calculated as a function of the layered parameters and the ratio of the radii of the two disks. Using a dyadic Green's function formulation for horizontally stratified media and the vector Hankel transform, the mixed boundary value problem is reduced to a set of coupled vector integral equations. Employing Galerkin's method in the spectral domain, the complex resonant frequencies are calculated and convergence of the results is demonstrated. It is shown that for each mode, the stacked circular microstrip structure has dual resonant frequencies which are associated with the two coupled constitutive resonators of the structure and which are a function of the mutual coupling between them. This mutal coupling depends on the geometrical configuration of the stacked structure, the layered parameters, and the disk radii. The maximum coupling effect occurs where the real parts of the resonant frequencies of the constitutive resonators are approximately equal, where the behavior of the resonances in this region is a function of the coupling. The dual frequency behavior of the stacked microstrip structure, easily controlled by varying the parameters of layer 2 and disk radii ratio, given fixed parameters for layer 1 and layer 3, may be used to broaden the bandwidth or provide for dual frequency use of the antenna.

We rigorously analyze the radiation problem of a circular patch which is center fed by a coaxial-line driven probe over a ground plane and situated in an arbitrary layered medium. The current distribution on both the patch and the probe is rigorously formulated using a planar stratified medium approach. A set of three coupled integral equation is derived which governs the axial current distribution on the probe, the radial current distribution on the patch and the azimuthal magnetic current sheet across the aperture of the driving coaxial line. This set of equations is then solved using the method of moments. The resulting matrix equation is obtained in terms of Sommerfeld-type integrals that take into account the effect of the layered medium. These integrals are efficiently computed by a simple deformation in the complex wavenumber domain. The probe current distribution, input impedance and radiation pattern are presented and compared to the case of a uniform probe current distribution.

We rigorously analyze the radiation problem of a circular patch which is center fed by a coaxial-line driven probe over a ground plane in an arbitrary layered medium. We formulate the problem in terms of a Weber transform which allows one to develop the Green's function of the layered medium with the probe and the microstrip patch as part of the medium. Using the Weber transform, automatically enforces the boundary conditions on the probe and the patch. This allows one to cast the problem as the solution of a set of two coupled integral equations governing the tangential component of the electric field across the aperture of the coaxial line feed and that across the interface where the patch lies. This set is then solved using the method of moments. The current distribution on both the probe and the patch is then computed from the component of the magnetic field tangential to their surfaces. Furthermore, from the computed electric field across the aperture of the coaxial line feed, one obtains the reflection coefficient for the TEM mode which allows one to compute the input impedance across the terminals of the probe. The probe current distribution, input impedance and radiation pattern are presented and the obtained results are compared with those using the three coupled integral equations and stratified medium.

Microstrip antennas of stacked configurations have received attention in recent years for both wideband and dual frequency use, overcoming the narrow bandwidth of conventional single layer microstrip antennas. Although much experimental work has been performed, theoretical analyses of stacked microstrip patches is limited. Resonant frequencies of the stacked microstrip antennas have been rigorously calculated. Numerical methods have been used to calculate the current and radiation fields of a stacked microstrip antenna. The method of moments has been applied to analyze to the stacked microstrip structure when excited by an incident plane wave. A spectral domain iterative analysis for a stacked microstrip antenna where the antenna is described by a rectangular sampling grid has been used to calculate radiation patterns. This analysis does not allow for accurate modeling of the probe feed.

In this work, the input impedance and radiation fields of a coaxial probe-fed microstrip antenna consisting of two circular microstrip disks in a stacked configuration are investigated. Using a dyadic Green's formulation, a rigorous analysis of the microstrip antenna is performed for two stacked configurations. Assuming uniform current along the probe, the mixed boundary value problem is reduced to a set of coupled vector integral equations using the vector Hankel transform and solved using Galerkin's method in the spectral domain. Due to the singular nature of the current on the driven disk in the vicinity of the probe, an additional term is included in the current expansion to account for the divergent nature of the current near the probe feed junction and insure continuity of the current at the junction.

The input impedance and radiation patterns of the stacked microstrip antenna is calculated as a function of the layered substrate, permittivities and thicknesses, and the ratio of the radii of the two disks. Both dual frequency and wideband operation is discussed.

Microstrip discontinuities, such as open end, gap and step in width, have been widely studied by many authors. There are different methods for analyzing microstrip discontinuities, such as quasi-static approach, planar waveguide model and integral equation formulation. As the frequrncy gets higher, the quasi-static assumption is not valid. In the planar waveguide model analyses, the thickness of the substrate is assumed much smaller than the wavelength so that a two-dimensional model may be applied. In this case, the effect of the radiation and the surface waves are not considered. The integral equation method has been applied to study the open end and gap dicontinuities on isotropic substrates. In applying the integral equation method, various approximation were introduced in the computation procedure. More recently, finite element expansion currents are used to formulate a full-wave analysis of micristrip discontinuities on isotropic substrates.

The open end, gap and step in width discontinuities placed on anisotropic substrates are rigorously analyzed. Both uniaxial and tilted uniaxial anisotropy are considered. The materials are assumed to be lossless and the metal strips to be infinitely thin. A dyadic Green's function for layered anisotropic media is used to formulate a set of vector integral equations for the current distribution. The fundamental hybrid mode is assumed to be propagating on the input and output of microstrip lines. In solving the set of vector integral equations, the method of moment is employed. The basis functions for the current on the metal strip consider the edge effect. Both logitudinal and transverse currents are considered in the calculation. The propagation constant for the infinitely long uniform microstrip line is first calculated. Then the propagation constant of the fundamental mode is used to formulate the excitation of the discontinuity problem. At the discontinuity, local basis functions are used to simulate the local currents near the discontinuity. The scattering matrix can then be obtained, and an equivalent circuit model can be proposed. The effect of the anisotropy is investigated and the results are discussed.

The leakage phenomenon is important in the area of millimeter-wave integrated circuits and integrated optics. Theoretical analyses and experiments have been performed to investigate this phenomenon. The leakage is due to the TE-TM coupling occurring at the geometrical discontinuities, and the leaky power in the form of surface wave propagates in the background medium.

There are different methods to analyze the dielectric strip waveguides, including the approximate field matching method, effective dielectric constant (EDC) method, mode matching method, etc. The first two methods are approximate, and can not be used to predict the imaginary part of the propagation constant. In the third one, ground planes have to be put at some distance away from the guiding structure, hence the effect of radiation loss is neglected.

In this work, an integral equation formulation using dyadic Green's function is derived to solve for the dispersion relation of single and coupled dielectric strip waveguides. A method to predict the leakage is presented, and the leakage properties are investigated.

Three different dielectric strip waveguides are investigated : optical rib waveguide, strip dielectric guide, and insulated image guide. Both single and coupled strip waveguides are studied. The cross section of the dielectric strips are assumed to have rectangular shape. Applying the Galerkin's method, the field distribution on the cross section are represented by a set of unit pulse basis functions. Substituting these basis functions into the integral equations, and choosing the same set of basis functions as the testing functions, we can obtain a determinant equation from which the propagation constant can be solved.

For single dielectric strip waveguide, it is observed that the leakage occurs when the effective refractive index is smaller than that of a surface wave mode in the background medium. It is also observed that if the lowest TE-like (TM-like) mode is leaky, the lowest TM-like (TE-like) mode is non-leaky. When the lowest order mode leaks, the surface wave mode of opposite polarization is excited. When the higher order mode leaks, the surface wave modes of both polarizations can be excited.

For two symmetrical dielectric strip waveguides, both the even and odd modes are investigated. For the leaky mode, the total leakage is due to the leakage from each individual strip waveguide. At the separation where the even mode has a maximum leakage, it implies that the surface wave modes excited by each waveguide add in phase. For the odd mode at about the same separation, these surface wave modes add out of phase, hence a null in the leakage is observed.

We rigorously analyze the problem of a circular microstrip disk on a thick dielectric substrate, fed by an eccentric probe. The problem is formulated in terms of a Vector Weber Transform which allows one to develop the Green's function of the layered medium with the eccentric probe and the microstrip patch as part of the medium. Using the Vector Weber Transform automatically enforces the boundary conditions on the probe and the patch. This allows one to cast the problem as the solution of a set of two coupled vector integral equations governing the tangential components of the electric field across the aperture of the coaxial line feed and those across the interface where the patch lies. This set is then solved using the method of moments where the magnetic frill current across the aperture of the coaxial line is represented by a Vector Weber Series expansion. From the computed electric field across the aperture of the coaxial line feed, the reflection coefficient for the TEM mode is obtained which allows one to compute the input impedance at the terminals of the probe. Numerical results for the input impedance are presented.

A finite difference time domain technique for two dimensional time domain scattering of electromagnetic waves is presented. The triangular grids and the control region approximation are employed to discretize Maxwell's equations. The finite difference time domain techniques with uniform rectangular grids has been used in the past. The scatterers are modeled using staircases and, recently, the accuracy of this approximation has been investigated. Several types of other grids have been proposed to improve the staircase approximation. Generalized nonorthogonal grid can model scatterer without staircasing. It has been applied to spherical systems, yet they appear to be cumbersome for general scatterers. The "distorted rectangular grid" model approximates the computational domain using rectangular grids and distorts the boundary grids to fit the interfaces. The triangular grid is used in this paper, which is very flexible in dealing with arbitrary scatterers and absorbing boundaries.

The control region approximation, which calls for Delaunay and Dirichlet tessellation, has been successfully applied to the frequency domain problems in the past. Two double integral terms are obtained by integrating the Helmholtz equation about the Delaunay tessellation. The term involving the Laplace operator can be converted to a closed loop integral of normal derivatives, which can easily be approximated in finite difference manner by utilizing the orthogonal property of Delaunay and Dirichlet tessellation. The remaining term can be approximated by multiplying the field at the node with the area. In the time domain problem, the same approximation is applied to the wave equation, except the term involving time derivatives is used in time marching scheme. Alternatively, as in Yee's algorithm, the first order Maxwell's equations are solved by spatially and temporally separating the electric and magnetic fields. In the case of electric polarization, the electric fields are placed at the nodes and the magnetic fields are placed at the center of triangular edges. The curl H equation is integrated by applying Stoke's theorem and convert it to a closed loop integral of tangential magnetic fields. This equation can be used to advance electric fields in time. To update magnetic fields, the second curl equation is used. This equation is approximated in the finite difference manner by utilizing the orthogonality property of the tessellation. The equations for the magnetic polarization case can also be derived following the similar procedure.

In order to limit the computation domain, the scatterers are enclosed with artificial outer boundaries. Continuous smooth outer boundaries, such as circles and ellipses, are chosen. The second-order time domain absorbing boundary conditions derived from the pseudo-differential operator approach is imposed at the outer boundaries. These boundary conditions are implemented with the control region approximation to determine necessary field quantities at the boundary. The results of the time domain control region approach are presented for simple scatterer geometries, such as conducting and coated cylinders and strips, by calculating both the transient and time-harmonic responses.

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 until recently it was used to obtain frequency characteristics of microstrip cavities. Also, it has been extended to the analyses of open microstrip line and microstrip discontinuity problems wher absorbing boundary conditions are needed for the simulation of the unbounded domain. However, only isotropic or simple anisotropic media are considered in the above papers.

A new FD-TD grid model is used to solve microstrip problems in anisotropic media having tilted optical axes expressed by permittivity or permeability tensor with off-diagonal elements. This grid model is indeed a superposition of two conventional grids with some displacement which depends on the optical axes of anisotropy. Implementations of different boundary conditions are discussed. Using this model, the frequency-dependent characteristics of microstrip lines are investigated. The microstrips are assumed to be placed on top of anisotropic substrates with tilted optical axes. The case with superstrates is also investigated.

In the finite difference computation, the open-end termination is simulated by using the open-circuit, short-circuit technique. The source plane is implemented by using a magnetic wall with a Gaussian pulse excited on the surface under the strip. Because of the symmetry of the problem, the region under consideration can be reduced by half, using a magnetic-wall at the center plane.

The fields at different positions are first calulated. Then the Fourier Transform is taken to give the field spectra from which the voltage and current can also be obtained. Using these data, the effective permittivity and the characteristic impedance can be determined. The frequency characteristics of microstrip lines in anisotropic media obtained by this method are compared with the published results.

Finite difference time domain (FDTD) techniques show great promise in their ability to solve three dimensional problems with arbitrary geometry. Advantages of this method include the ability to model spatially or temporally varying media. These advantages are due to the complete discretization of both space and time. Considering the volume of information being calculated these techniques are very efficient and are well suited to calculation on future parallel processing computers. This method was first formulated by Yee in 1966 and his basic algorithm is still in use. Recent work has demonstrated the applicability of the FDTD technique to microstrip problems. The centered finite difference approximations used are second order accurate in both space and time yielding good results for reasonable mesh sizes. Numerical techniques used to solve electromagnetic problems must limit the domain over which the fields are to be calculated. This mandates the use of an absorbing boundary condition to simulate the outward propagation of waves incident on the walls of the mesh. An absorbing boundary condition has been developed by Mur based on the work of Enquist and Majda.

Our work in this area includes development of the algorithms mentioned above into a general purpose computer code which may be used to solve for the transient response of electromagnetic problems with an arbitrary geometry. In addition to the transient response, frequency domain parameters may be obtained by fourier transform of the time domain results. Since the fields are calculated throughout space and time all other desired parameters may be calculated from the field quantities. Specifically, we are analyzing rectangular microstrip structures with as many as two or more ports. Such structures may be used in MMIC filters or antennas. This problem is of interest for several reasons. First, there are existing frequency domain solutions to the resonance problem of a rectangular microstrip patch, which we may compare with the FDTD solution. Secondly, the FDTD technique may be used to analyze coupling of microstrip lines to the rectangular structure. This coupling may be either a direct connection or a gap coupled connection. Advantages of the FDTD solution of this problem are that it is a full wave solution which allows for radiation or surface wave loss and that no empirical values such as "effective" dimensions are needed for the analysis, also the geometry may be altered easily to allow for various connections or coupling to the patch. This is a significant improvement over methods which rely on a planar circuit approach in which the substrate thickness must be small compared to wavelength and inherently three dimensional coupling problems are not easily handled. Comparison of our results with various planar circuit approaches will be made.

A new perturbation series, coupled integral equation approach for calculating the frequency dependent circuit parameters for quasi-TEM transmission lines with lossy conductors is presented. The method considers the addition of loss and dispersion to be perturbations on the lossless TEM case, and therefore the difference between the propagation constant and the wavenumber in free space is a small parameter. We obtain the lowest order term of the perturbation series by solving two quasistatic problems; the electrostatic problem to get the capacitance, and the magnetoquasistatic problem, with the distribution of current inside the wire considered, which gives the frequency-dependent inductance and resistance. Both of these problems are solved using one-dimensional integral equations for quantities on the surface of the conductor; this represents a significant improvement in efficiency over previous methods. For most cases of practical interest, the lowest order term of the series will suffice. If, however, the change in the propagation constant from the lossless case, due to the altered inductance and the addition of resistance, is significant, additional terms in the perturbation series can be calculated.

The method is illustrated with the case of one or more wires embedded in a uniform dielectric. In the original magnetoquasistatic problem, the current is entirely directed along the axis of propagation, and satisfies the frequency-domain diffusion equation. Outside the wire, the magnetic vector potential is in the same direction, and obeys Laplace's equation. The boundary conditions are the continuity of tangential and normal magnetic field at the interface, which can be expressed in terms of the current density and vector potential and their derivatives. Since we can express the ratio of the frequency-dependent resistance to the DC resistance in terms of the values of the volume current and its normal derivative on the surface of the wire only, we can use a pair of coupled integral equations to solve for these quantities alone, which we can solve by Galerkin's method or other finite element methods.

Results obtained using this technique are shown for some important cases, including rectangular wires, and are compared with earlier methods and with experimental data. Previous methods for calculating the resistance fall into three categories. First, for certain cases, exact analytical results can be obtained. Secondly, especially in the case of a rectangular wire, the cross-section can be divided into rectangular segments, each much smaller than a skin-depth, across which the current is assumed to be constant. Magnetoquasistatics gives simple answers for the resistance and self-inductance of each element, and the mutual inductance between elements. This leads to a matrix equation which is solved for the current distribution. The disadvantages of this technique are that it requires basis functions throughout the cross-section of the conductor, which is especially intensive as the frequency gets large. Also, closed form expressions for the matrix elements only exist when the elements are rectangular — other shapes, such as triangular patches, which might be used to fit a wire of arbitrary shape, lead to nested numerical integrals.

The third method used is a variational procedure. This is similar to the method presented here, except that the current and the magnetic vector potential are expanded in functions which span the entire cross-section. This has two drawbacks: first, it requires that there be a closed outer conductor, which is not physical in many important cases. Second, as in the previous method, using elements which fill the entire cross-section increases the computation time unnecessarily, since only the value of the current and its normal derivative at the surface of the wire are needed to calculate the resistance.

A new method for analyzing frequency-dependent transmission line systems with nonlinear terminations is presented. The generalized scattering matrix formulation is used as the foundation for the time domain iteration scheme. Compared to the admittance matrix approach proposed in a previous paper, it has the advantage of shorter impulse response which leads to smaller computer memory requirement and faster computation time. Examples of a microstrip line loaded with nonlinear elements are given to illustrate the efficiency of this method.

As the speeds of integrated circuits increase, the effect of interconnection lines becomes more and more important. Traditional lumped element circuit model must be supplemented by the transmission line model in order to account for propagation delays, dispersion and losses. This has created needs for new numerical procedures that can be easily incorporated into current CAD tools. To make matters more complicated, the interconnection lines are terminated with not only linear resistors but also nonlinear semiconductor devices, such as diodes and transistors.

Several techniques are now commonly used to deal with nonlinear circuit problems, for example, the direct time domain approaches, and the semi-frequency-domain approaches, such as the harmonic balance technique. The semi-frequency-domain approaches are useful for microwave and millimeter wave integrated circuits but become impractical for digital integrated circuits because of the latter's wide band nature. On the other hand, frequency-dependent parameters often make it awkward to apply the direct time domain approach to the interconnection line systems.

We propose a hybrid frequency-domain time-domain technique based on the generalized scattering matrix formulation. For an n line system, we define $2n$ scattering parameters according to the frequency-dependent characteristic impedances of individual lines ($Z_{0j} = \sqrt{L_{jj}(\omega)/C_{jj}(\omega)}$). The time-domain transfer matrix (impulse response) of this $2n$-port system is then obtained by the inverse Fourier Transform. Lastly, the nonlinear equations associated with terminal characteristics are incorporated and solved with iteration procedures such as the Newton-Ralphson method.

The key to efficient and stable solutions in this problem is shortening the duration of every transfer matrix element. With the generalized scattering parameters approach, we are able to achieve that yet eliminating the need for artificial matching networks adopted by a previous work. Furthermore, the use of individual characteristic impedances in the definition of scattering parameters enables us to generalize this method to coupled lines with distinct properties while keeping the duration of transfer matrix elements short. This cannot be realized if traditional scattering parameters are used. We shall illustrate the elegance and efficiency of our approach for a dispersive microstrip line with different nonlinear loads and excited with narrow Gaussian pulses. The elements of transfer matrix are found out to be either zero or single retarded delta-impulse accompanying a small spike with very narrow spread. Typical computation time for a 1000 time-step iteration ranges from 4 to 27 seconds on a VAXStation 3500. The effects of line dispersion and load nonlinearity will be clearly delineated in the presentation.

The transient propagation characteristics of VLSI interconnects with discrete capacitive loads at various locations is analyzed based on a hybrid transmission lines-lumped element circuit model. Exact expressions of the Laplace transform of unit step responses are first obtained through the ABCD matrix formulation. We then apply the equivalent dominant pole approximation to the transfer function with the propagation delays factored out. The approximated transfer function can be inverted in closed form and quickly evaluated. These results provide efficient ways of finding approximately the effects on delays and rise time brought by VLSI off-chip interconnects.

Because of the dramatic increase in device densities on microelectronic chips, the propagation delay for off-chip interconnects has become the limiting factor to the speed of VLSI packages. Typical scales of these interconnects will be comparable or larger to the characteristic wavelength of high frequency components of the signal. Therefore, to calculate the delays caused by these interconnects properly, a hybrid circuit model containing transmission line sections as well as lumped elements must be used in place of the all-lumped element one. Most circuit simulation packages are nevertheless based on the latter and have to resort to subsection approximation when dealing with transmission lines. This scheme will undoubtedly lead to lengthy computation, which is not desirable when a quick, heuristic estimate of bounds are needed for the initial phase of the design cycle.

Two approaches have been developed for obtaining the approximate transient response without lengthy simulation. The first kind of solution techniques emphasize the calculation of bounds to voltage responses from the differential equations either by direct integration or by using the optimal control theory. On the other hand, the second kind of techniques analyze the properties of Laplace transform domain solution. Thus far, their applications are limited to all lumped-element and distributed RC networks, which can only take care of on-chip interconnects. We shall take the second approach by incorporating transmission line elements for off-chip delay estimation.

Our configuration includes a series of transmission line sections with arbitrary discrete capacitances and resistances loaded at junctions. The ABCD matrix formulation is used to obtain the Laplace transform of the unit step response. We express the latter in the form of $\exp(-sT)/Q(s)$, where $Q(s) = A_0(s) + A_1(s)\exp(s\tau_1) + A_2(s)\exp(s\tau_2) + \cdots$ with all $\{A_i(s)\}$ being rational functions in s. The factor $\{\exp(-sT)\}$ is identified with direct transmission delay over the total length of the line. For the rest part $(1/Q(s))$, we proceed to apply the equivalent dominant pole approximation technique[7]. Either a single negative real pole or second-order complex conjugate pair will be chosen for approximation depending upon the property of lumped loads at junctions as well as the source impedances. A phase-correction factor $\exp(-sT_m)$ is introduced to make up for the discrepancies caused by our low-order approximation. The first-order and second order approximations enable us to obtain closed-form solution to the transient response. Comparison of the approximated responses with those obtained from brute-force numerical Laplace inversion shows very good match when the propagation delay of an average transmission line section is less than half the product of junction load capacitance and transmission line characteristic impedance. Yet we only have to spend a fraction of the time for computations. The accuracy of this method will be discussed in detail with some examples of lossless transmission line networks in which lumped capacitors are loaded at regular intervals.

The propagation properties of single and coupled inhomogeneous slab waveguides are analyzed. An integral equation formulation using the dyadic Green's function which covers both the TE and TM modes is proposed. The dispersion relations are obtained by applying the Galerkin's method to solve the integral equation. The coupling between two symmetrical inhomogeneous slab waveguides is also investigated. This method is shown to be applicable to arbitrary dielectric constant profiles.

The guidance and leakage properties of single and coupled dielectric strip waveguides are analyzed using the dyadic Green's function and integral equation formulation. Galerkin's method is used to solve the integral equation for the dispersion relation. The effects of the geometrical and the electrical parameters on the dispersion relation are investigated. A method to predict the occurrence of leakage is proposed. The properties of the even and the odd leaky modes are also investigated. Results are compared with previous analysis and shown to be in good agreement.

A spectral domain dyadic Green's function for multilayered uniaxially anisotropic media containing three-dimensional sources is derived. Tractable forms are shown to be easily deduced from the physical picture of the waves radiated by the primary sources and the multiple reflections from the stratified medium. The formulation decomposes the dyadic Green's function into TE and TM waves. The dyadic Green's function in the source region is properly represented by extracting the delta function singularity. A simple proceedure to obtain the fields in any arbitrary layer is described. Recursion relations for appropriately defined reflection and transmission coefficients are presented. Forms suitable for transmission line applications in multilayered media are derived.

Full modal analysis is used to study the dispersion characteristics of microstrip lines periodically loaded with crossing strips in a stratified uniaxially anisotropic medium. Dyadic Green's functions in the spectral domain for the multilayered medium in conjunction with the vector Fourier transform (VFT) are used to formulate a coupled set of vector integral equations for the current distribution on the signal line and the crossing strips. Galerkin's procedure is applied to derive the eigenvalue equation for the propagation constant. The effect of anisotropy for both open and shielded structures on the stopband properties is investigated.

A direct three dimensional finite difference time domain (FDTD) method is applied to the full-wave analysis of various microstrip structures. The method is shown to be an efficient tool for modelling complicated microstrip circuit components as well as microstrip antennas. From the time domain results, the input impedance of a line-fed rectangular patch antenna and the frequency dependent scattering parameters of a low pass filter and a branch line coupler are calculated. These circuits are fabricated and the measurements are compared with the FDTD results and shown to be in good agreement.

A rigorous dyadic Green's function formulation in the spectral domain is used to study the dispersion characteristics of signal strip lines in the presence of metallic crossing strips. A set of coupled vector integral equations for the current distribution on the conductors is derived. Galerkin's method is then applied to derive the matrix eigenvalue equation for the propagation constant. The dispersion properties of the signal lines are studied for both cases of finite and infinite length crossing strips. The effects of the structure dimensions on the passband and stopband characteristics are investigated. For crossing strips of finite length, the stopband is mainly affected by the period, the crossing strip length, and the separation between the signal and the crossing strips. For crossing strips of infinite length carrying travelling waves, attenuation along the signal line exists over the whole frequency range of operation.

A new method for analyzing frequency-dependent transmission line systems with nonlinear terminations is presented. The generalized scattering matrix formulation is used as the foundation for the time domain iteration scheme. Compared to the admittance matrix approach proposed in a previous paper, it has the advantage of shorter impulse response which leads to smaller computer memory requirement and faster computation time. Examples of a microstrip line loaded with nonlinear elements are given to illustrate the efficiency of this method.

PUBLICATIONS SUPPORTED BY ONR CONTRACT N00014-89-J-1019 SINCE 1988

Inversion of permittivity and conductivity profiles employing transverse-magnetic polarized monochromatic data (T. M. Habashy, M. Moldoveanu, and J. A. Kong), SPIE's 1990 International Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, California, July 8 – 13, 1990.

Analysis of Diffraction from Chiral Gratings (S. H. Yueh and J. A. Kong), accepted for publication in *Journal of Electromangetic Waves and Applications.*, 1990.

Input Impedance of a Probe-Fed Stacked Circular Microstrip Antenna (A. N. Tulintseff, S. M. Ali, and J. A. Kong), accepted for publication in *IEEE Transactions on Antennas and Propagation.*

Resonant Frequencies of Stacked Circular Microstrip Antennas (A. N. Tulintseff, S. M. Ali, and J. A. Kong), *IEEE AP-S International Symposium and URSI Radio Science Meeting,* San Jose, California, June 26-30, 1989.

Probe Excitation of a Center-Fed Circular Microstrip Antenna Employing a Stratified Medium Formulation (S. M. Ali, T. M. Habashy, and J. A. Kong), *IEEE AP-S International Symposium and URSI Radio Science Meeting,* San Jose, California, June 26-30, 1989.

Probe Excitation of a Center-Fed Circular Microstrip Antenna Employing the Weber Transform (T. M. Habashy, S. M. Ali, and J. A. Kong), *IEEE AP-S International Symposium and URSI Radio Science Meeting,* San Jose, California, June 26-30, 1989.

Input Impedance and Radiation Fields of a Probe-Fed Stacked Circular Microstrip Antenna, (A. N. Tulintseff, S. M. Ali, and J. A. Kong), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25–26, 1989.

Analysis of Microstrip Discontinuities on Anisotropic Substrates, (J. Xia, S.M. Ali, and J. A. Kong), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25–26, 1989.

Analysis of Dielectric Strip Waveguides Using Integral Equation Formulation, (J. F. Kiang, S. M. Ali, and J. A. Kong), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25–26, 1989.

Input Impedance of a Circular Microstrip Antenna Fed by an Eccentric Probe, (S.M. Ali, T.M. Habashy, and J.A. Kong), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25–26, 1989.

Finite Difference Time Domain Techniques for Two Dimensional Triangular Grids, (Check F. Lee, Robert T. Shin, Jin A. Kong, and Brian J. McCartin), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25–26, 1989.

Absorbing Boundary Conditions on Circular and Elliptic Boundaries, (Check F. Lee, Robert T. Shin, Jin A. Kong, and Brian J. McCartin), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25–26, 1989.

A New Finite-Difference Time-Domain Grid Model for Microstrip Problems in Anisotropic Media, (C. W. Lam, S. M. Ali, and J. A. Kong), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25–26, 1989.

Analysis of Multiport Rectangular Microstrip Structures using a Three Dimensional Finite Difference Time Domain Technique, (D. M. Sheen, S. M. Ali, M. D. Abouzahra, and J. A. Kong), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25–26, 1989.

The Frequency-Dependent Resistance of Conductors with Arbitrary Cross-Section, (M. J. Tsuk and J. A. Kong), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25–26, 1989.

Transient Analysis of Frequency-Dependent Transmission Lines with nonlinear Terminations, (Qizheng Gu, Y. Eric Yang and Jin Au Kong), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25–26, 1989.

Transient Analysis of Capacitively Loaded VLSI Off-Chip Interconnections, (Y. Eric Yang and Jin Au Kong), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25–26, 1989.

Input Impedance of a Circular Microstrip Antenna Fed by an Eccentric Probe (S. M. Ali, T. M. Habashy, and J. A. Kong), *Progress in Electromagnetics Research Symposium,* Boston, Massachusetts, July 25-27, 1989.

Resonant frequencies of stacked circular microstrip antennas (A. N. Tulintseff, S. M. Ali, and J. A. Kong), *IEEE Transactions on Antennas and Propagation,* submitted for publication.

Integral Equation Formulation of Inhomogeneous Slab Waveguides (J. F. Kiang, S. M. Ali, and J. A. Kong), *IEEE Journal of Quantum Electronics,* submitted for publication.

Integral Equation Solution to the Guidance and Leakage Properties of Coupled Dielectric Strip Waveguides, (J. F. Kiang, S. M. Ali, and J. A. Kong), *IEEE Transactions on Microwave Theory and Techniques,* Vol. 38, No. 2, 193–203, February 1990.

Dyadic Green's Functions for Multilayered Uniaxially Anisotropic Media (S. M. Ali, T. M. Habashy, and J. A. Kong), *Journal of Electromagnetic Waves and Applications,* submitted for publication.

The Propagation Characteristics of Signal Lines with Crossing Strips in Multilayered Anisotropic Media (C. W. Lam, S. M. Ali, and J. A. Kong), *Journal of Electromagnetic Waves and Applications,* Vol. 4, No. 10, 1005–1021, 1990.

Application of the Three Dimensional Finite Difference time- domain method to the analysis of planar microstrip circuits (D. M. Sheen, S. M. Ali, M. D. Abouzahra, and J. A. Kong), *IEEE Transactions on Microwave Theory and Techniques,* Vol. 38, 849 – 857, July 1990.

Propagation properties of strip lines periodically loaded with crossing strips (J. F. Kiang, S. M. Ali, and J. A. Kong), *IEEE Transactions on Microwave Theory and Techniques,* Vol. 37, No. 4, pp. 776–786, April 1989.

Transient Analysis of frequency-dependent transmission line systems terminated with nonlinear loads, (Q. Gu, Y. E. Yang, and J. A. Kong), *J. of Electromagnetic Waves and Applications,* Vol. 3, No. 3, 183–197, 1989.

Office of Naval Research

DISTRIBUTION LIST

Arthur K. Jordan

›de: 1114SE 'fice of Naval Research ›0 North Quincy Street ·lington, VA 22217	3 copies
›ministrative Contracting Officer .9-628 ›ssachusetts Institute of Technology ›mbridge, MA 02139	1 copy
.rector ›val Research Laboratory ›shington, DC 20375 :tn: Code 2627	6 copies
›fense Technical Information Center ›dg. 5, Cameron Station ›exandria, VA 22314	2 copies