Section 3 Electromagnetics

Chapter 1 Electromagnetic Wave Theory and Applications

Chapter 1. Electromagnetic Wave Theory and Applications

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1.1 Electromagnetic Waves in Multilayer Media

Sponsors

Joint Services Electronics Program
  Contract DAAL03-89-C-0001
National Science Foundation
  Grant ECS 86-20029
Schlumberger-Doll Research
U.S. Army Research Office
  Contract DAAL03 88-K-0057
U.S. Navy - Office of Naval Research
  Contract N00014-90-J-1002

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Cylindrical microstrip antennas find many applications in high-speed aircraft and spacecraft because of their conformity with the aerodynamical structure of such vehicles. Recently, there has been some progress in the theoretical study of this kind of antenna. The radiation from the wraparound cylindrical microstrip element was computed using a magnetic wall cavity model. More recently, the radiation from the wraparound, and the rectangular patches was computed by assuming an electric surface current distribution on the microstrip

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patch. The excitation problem of realizing such a current distribution was not addressed in these investigations. Furthermore, the input impedance for the cylindrical microstrip antennas was not reported.

We addressed the more realistic problem of the radiation from a cylindrical microstrip antenna excited by a probe.[7] Both the cylindrical-rectangular and the wraparound elements are discussed. The current distribution on the patch is rigorously formulated using a cylindrically stratified medium approach. A set of vector integral equations is derived which governs the current distribution on the patch. This set of equations is then solved using a moment method in which the patch current is expanded in terms of a complete set of basis functions that can take into account the edge singularity condition. The input impedance together with the radiation pattern are derived both exactly and in the small substrate thickness limit where a single mode approximation is employed.

Frequency domain analytical work with complicated microstrip circuits has generally been done using planar circuit concepts in which the substrate is assumed to be thin enough that propagation can be considered in two dimensions by surrounding the microstrip with magnetic walls. Fringing fields are accounted for by using either static or dynamic effective dimensions and permittivities. Limitations of these methods are that fringing, coupling, and radiation must all be handled empirically since they are not allowed for in the model. Also, the accuracy is questionable when the substrate becomes thick relative to the width of the microstrip. To fully account for these effects, it is necessary to use a full-wave solution.

Finite difference time domain methods have recently been used to effectively calculate the frequency dependent characteristics of microstrip discontinuities. Analysis of the fundamental discontinuities is of great importance since more complicated circuits can be realized by interconnecting microstrip lines with these discontinuities and using transmission line and network theory. Some circuits, however, such as patch antennas, may not be realized in this way. Additionally, if the discontinuities are too close to each other the use of network concepts will not be accurate due to the interaction of evanescent waves. To accurately analyze these types of structures it is necessary to simulate the entire structure in one computation. The finite difference time domain (FDTD) method shows great promise in its flexibility to handle a variety of circuit configurations. An additional benefit of the time domain analysis is that a broadband pulse may be used as the excitation and the frequency domain parameters may be calculated over the entire frequency range of interest by Fourier Transform of the transient results.

The frequency dependent scattering parameters are calculated for several printed microstrip circuits, specifically, a line-fed rectangular patch antenna, a low pass filter, and a rectangular branch line coupler.[8] These circuits represent resonant microstrip structures on an open substrate, hence, radiation effects can be significant, especially for the microstrip antenna. Calculated results are presented and compared with experimental measurements.

Finite difference techniques have been applied to analyze various electromagnetic problems in both frequency and time domains. Examples of these applications include scattering and radiation, microwave and millimeter wave circuits, and hyperthermia. Besides the widespread applications, the latest research efforts have been directed at achieving more accurate discretization schemes, improving absorbing boundary conditions for open region problems, and efficient implementations on supercomputers. We investigated three topics relevant to the finite difference technique: absorbing boundary conditions, spatial discretization, and time domain model of dispersive materials.

The absorbing boundary conditions on circular and elliptical boundaries are investigated.[9] The absorbing boundary conditions are crucial for open region problems such as scattering and radiation. The absorbing boundary conditions are used to simulate the unbounded space, and hence, provide

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[7] T.M. Habashy, S.M. Ali, and J.A. Kong, "Input Impedance Parameters and Radiation Pattern of Cylinderical-Rectangular and Wraparound Microstrip Antennas," *IEEE Trans. Antennas Propag.* 38(5): 722-731 (1990).

[8] D.M. Sheen, S.M. Ali, M.D. Abouzahra, and J.A. Kong, "Application of the Three Dimensional Finite Difference Time-Domain Method to the Analysis of the Planar Microstrip Circuits," *IEEE Trans. Microwave Theory Tech.* 38(7): 849-857 (1990).

[9] C.F. Lee, R.T. Shin, and J.A. Kong, "Fine Difference Method for Electromagnetic Scattering Problems," In *Progress In Electromagnetics Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 4, Ch. 11, pp. 373-442; C.F. Lee, R.T. Shin, J.A. Kong, and B.J. McCartin, "Absorbing Boundary Condions on Circular and Elliptic Boundaries," *J. Electromag. Waves Appl.* 4(10): 945-962 (1990).

finite computational domain for open region problems. The size of the computational domain is directly related to the absorbability of the absorbing boundary condition. The absorbing boundary condition is derived by factorizing the wave equation using pseudo-differential operator technique. The factorization scheme presented by Engquist and Majda is modified to derive absorbing boundary conditions for circular and elliptical boundaries. In the case of circular boundary, the modified factorization scheme yields results equivalent to that of Bayliss and Turkel. In the case of elliptical boundary, the absorbing boundary condition is derived and numerically demonstrated to be efficient in reducing the size of the computational domain for elongated scatterers.

FD-TD scheme on triangular grids is discussed. The discretization scheme is crucial in geometrical modeling, treating dielectric/magnetic materials, and efficient implementation. The discretization scheme is based on the combination of the finite difference and control region approximations. The flexibility of the triangular grid is utilized to provide accurate geometrical modeling. It is demonstrated that the FD-TD technique on triangular grid provides more accurate target modeling capability than the traditional FD-TD technique of the rectangular grid.

An efficient FD-TD algorithm for treating frequency dispersive material is presented. Accurate and efficient time domain model of dispersive materials is very important in time domain analysis. Accurate time domain results cannot be obtained unless the dispersive nature of the material is properly modeled. The traditional model of the dispersive characteristic is based on the time domain convolution integral which requires large memory and long computation time. A more recent model is based on the exponential approximation of the time domain response of the material. In this section, we model the dispersive characteristics using ordinary time differential equations and provide an efficient discretization scheme.

For microwave integrated circuit applications, the characteristics of interconnects have been investigated for propagation modes, time response, crosstalk, coupling, delay, etc. In these analyses, it is assumed that quasi-TEM modes are guided along the multiconductor transmission line. 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. However, the infinite extent of the structure was incorporated, but only a two-layer medium was considered.

A quasi-TEM analysis of coupled lossy microstrip lines of finite strip thickness embedded in different layers of a lossy isotropic stratified medium is presented.[10] First, a spectral domain scalar Green's function in a lossy isotropic stratified medium is derived. Based on the scalar Green's function, a set of coupled integral equations is obtained for the charge distribution on the strip surfaces. The method of moments is then applied where 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 problem 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 the multiconductor line, 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.

A full modal analysis is used to study the dispersion characteristics of microstrip lines periodically loaded with crossing strips in a stratified uniaxially anisotropic medium.[11] 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

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[10] J.F. Kiang, S.M. Ali, and J.A. Kong, "Modelling of Lossy Microstrip Lines with Fine Thickness," *Progress In Electromagnetics Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 4, Ch. 3, pp. 85-117.

[11] C.W. Lam, S.M. Ali, and J.A. Kong, "The Propagation Characteristics of Signal Lines with Crossing Strips in Multilayered Anisotropic Media," *J. Electromag. Waves Appl.* 4(10): 1005-1021 (1990).

and shielded structures on the stopband properties is investigated.

The excitation of the earth-ionosphere waveguide by point dipoles at satellite heights was studied by Einaudi and Wait. In their formulation, the ionosphere was crudely modeled as a single D-layer, moreover the geomagnetic field was assumed to be vertical, thus rendering the validity of the model to polar regions. Then, a more general analysis was performed where the geomagnetic field was assumed to be arbitrarily-oriented and the earth to be curved along the direction of propagation. However, the ionosphere was assumed to be a semi-infinite homogeneous medium and the results presented in these papers were limited to a frequency of 75 Hz. Furthermore, in these papers an indirect scheme was employed to formulate the response of point dipole sources: the case of line quadrupole sources was first considered, and then at the end of the development, the results were converted to apply to a point source.

We presented a rigorous approach to the problem of radiation of electric or magnetic sources in a stratified arbitrary magnetized linear plasma.[12] The fields are obtained in terms of dyadic Green's functions of electric or magnetic type represented in the spectral domain. First, the dyadic Green's function for an unbounded arbitrary magnetized linear plasma is derived. The formulation is considerably simplified by using the kDB system of coordinates in conjunction with the Fourier transform. This leads to compact and explicit expressions for the dyadic Green's functions. The distributional singular behavior of the various dyadic Green's functions in the source region is investigated and taken into account by extracting the delta function singularities. Finally, the dyadic Green's function in any arbitrary layer is obtained in terms of appropriately defined global upward and downward reflection and transmission matrices. The field expressions for an arbitrary distribution of sources or linear antennas can be obtained by performing a convolution integral over the volume of the antenna weighted by the current density on the antenna.

The study of electromagnetic radiation from sources in the ionospheric plasmas has received much attention in the research on the satellite-borne antennas. For many years, special attention has been given to the radiation in the very low frequency (VLF) band due to its applications in the down-link communication systems. The far field pattern of a VLF phased array located in a magnetized plasma is studied.[13] The general principles of antenna array design in the anisotropic media are discussed. Special attention is drawn to the two-dimension planar array allowed to rotate with respect to an axis perpendicular to the plane of the array, and the main beam of which is kept in the same direction as that of the geomagnetic field line during the rotation. The applicability of the principle of pattern multiplication as well as the effects of different types of radiating elements for different k-surface geometries are investigated.

An inversion algorithm based on a recently developed inversion method referred to as the Renormalized Source-Type Integral Equation approach is presented.[14] 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 where the Born series diverges; hence, the name Renormalized Source-Type Integral Equation Approach.

There has been considerable interest in the theoretical study of scattering from chiral media. Chiral medium characterized by biisotropic constitutive relation is a special case of the bianisotropic medium whose electromagnetic properties have been extensively studied by Kong. Periodic gratings have been the object of extensive research through the years because of its many applications in distributed feedback laser, integrated optics, acousto-optics, quantum electronics, and holography. For the analysis of wave diffraction by periodic surface grating, methods including the method of moments and extended boundary condition method are rigorous and in general compu-

[12] T.M. Habashy, S.M. Ali, J.A. Kong, and M.D. Grossi, "Dyadic Green's Functions in a Planar Stratified, Arbrarily Magnetized Linear Plasma," *Radio Sci.*, forthcoming.

[13] C.H. Han, J.A. Kong, T.M. Habashy, and M.D. Grossi, "Principles of VLF Antenna Array Design in Magnetized Plasmas," URSI National Radio Science Meeting, Boulder, Colorado, January 3-5, 1990.

[14] T.M. Habashy, M. Moldoveanu, and J.A. Kong, "Inversion of Permtivy and Conductivy Profiles Employing Transverse-Magnetic Polarized Monochromatic Data," SPIE 1990 International Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, California, July 8-13, 1990.

tationally efficient. For the analysis of periodic slanted dielectric gratings, a coupled-wave method has been developed.

The coupled-wave theory is generalized to analyze the diffraction of waves by chiral gratings for arbitrary angle of incidence and polarizations.[15] 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 integral equation method has been used to solve for the dispersion relation of the rectangular dielectric waveguide.[16] This method incorporates the continuous spectrum, and hence the radiation loss is taken into account. However, no results concerning practical single and coupled dielectric strip waveguides were presented; and the leakage phenomenon was not investigated. We derived an integral equation formulation using the dyadic Green's function 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. The integral equation formulation for an arbitrary number of inhomogeneous dielectric strips is derived and Galerkin's method is used to obtain the matrix eigenvalue equations. Numerical results and discussions are presented.

A microstrip antenna consisting of two circular microstrip disks in a stacked configuration driven by coaxial probe excitation is considered.[50] 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.

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.

A new hybrid cross-section finite element/coupled integral equation method is presented,[17] which is both efficient and flexible in regards to the kinds of configurations which can be handled. 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 with triangular basis functions. For high frequencies, a coupled surface integral equation technique is used. For the intermediate frequency range, where the conductors are on the order of skin depth, we found it very

[15] S.H. Yueh and J.A. Kong, "Analysis of Diffraction from Chiral Gratings," *J. Electromag. Waves Appl.*, forthcoming.

[16] J.F. Kiang, S.M. Ali, and J.A. Kong, "Integral Equation Solution to the Guidance and Leakage Properties of Coupled Dielectric Strip Waveguides," *IEEE Trans. Microwave Theory Tech.* 38(2): 193-203 (1990).

[17] M.J. Tsuk and J.A. Kong, "A Hybrid Method for the Calculation of the Resistance and Inductance of Transmission Lines with Arbrary Cross-Sections," submitted to *IEEE Trans. Microwave Theory Tech.*

efficient to interpolate between the results of the cross-section and surface methods.

1.2 Remote Sensing of Earth Terrain

Sponsor

National Aeronautics and Space Administration
Grant NAGW-1617

Project Staff

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Accurate calibration of polarimetric radar systems is essential for the polarimetric remote sensing of earth terrain. A polarimetric calibration algorithm using three arbitrary in-scene reflectors is developed.[18] The transmitting and receiving ports of the polarimetric radar are modeled by two unknown polarization transfer matrices. These unknown matrices are determined using the measured scattering matrices from the calibration targets. A Polarization-Basis Transformation technique is introduced to convert the scattering matrices of the calibration targets into one of the six sets of targets with simpler scattering matrices. Then, the solution to the original problem can be expressed in terms of the solution obtained using the simpler scattering matrices. The uniqueness of polarimetric calibration using three targets is addressed for all possible combinations of calibration targets. The effect of misalignment of the calibration targets and the sensitivity of the polarimetric calibration algorithm to the noise are illustrated by investigating several sets of calibration targets in detail.

Classification of earth terrain within an image is one of the many important applications of polarimetric data. A systematic classification procedure will place the classification process on a more quantitative level and reduce the amount of photo-interpretation necessary. Both the supervised and unsupervised classification techniques are applied to San Francisco Bay and Traverse City Synthetic Aperture Radar (SAR) images, supplied by the Jet Propulsion Laboratory.[19] For supervised classification processing, the Bayes technique is used to classify fully polarimetric and normalized polarimetric SAR data. Simpler polarimetric discriminates, such as the absolute and normalized magnitude response of the individual receiver channel returns, in addition to the phase difference between the receiver channels, are also considered. An unsupervised technique, based on comparing general properties of the Stokes parameters of the scattered wave to that of simple scattering models, is also discussed . It is shown that supervised classification yields the best overall performance when accurate classifier training data are used, whereas unsupervised classification is applicable when training data are not available.

Classification or identification of radar targets from measurements of their radar signatures continues to be an area of considerable interest and active research. In the past, a variety of classification algorithms have been proposed, and these techniques have yielded varied levels of effectiveness in differing applications. One novel group of classification techniques which overcome the limitations of the conventional ones, and which has recently received considerable attention, is a set of methods based on the use of neural networks. The application of neural networks to the problem of target classification from high range resolution profiles is considered.[20] The effectiveness of the neural network classifier is demonstrated using synthetically generated range profiles of two groups of geometries, produced using RCS prediction techniques. For both groups, the neural network approach is compared with the conventional techniques of profile matching, and Euclidean and Mahalanobis distance classifiers. In addition, the performance of both conventional and neural network classifiers in the presence of additive noise and alignment uncertainty is explored. Finally, a comparison of the computational and storage requirements of each approach is presented.

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[18] S.H. Yueh, J.A. Kong, and R.T. Shin, "Calibration of Polarimetric Radars using In-Scene Reflectors," In *Progress In Electromagnetic Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 3, Ch. 9, pp. 451-510; S.H. Yueh, J.A. Kong, and R.T. Shin, "Calibration of Polarimetric Radars Using In-Scene Reflectors," Tenth International Geoscience and Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990.

[19] J.A. Kong, S.H. Yueh, H.H. Lim, R.T. Shin, and J.J. van Zyl, "Classification and Maximum Contrast of Earth Terrain Using Polarimetric Synthetic Aperture Radar Images," In *Progress In Electromagnetics Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 3, Ch. 6, pp. 327-370.

[20] R.G. Atkins, R.T. Shin, and J.A. Kong. "A Neural Net Method for High Range Resolution Target Classification," In *Progress In Electromagnetics Research,* ed. J.A. Kong. (New York: Elsevier, 1990), Vol. 4, Ch. 7, pp. 255-292.

Besides classifying earth terrain into different classes, there is also considerable interest in determining the optimal polarizations that maximize contrast between two scattering classes in polarimetric radar images. Contrast enhancement is a processing technique which modifies the input data structure so that either the human observer, computer, or other hardware devices can extract certain information from the processed data more readily after the change. We employed a Lagrange multiplier method which determines the transmitting and receiving polarization state which produces maximum contrast, or separation in the average intensity, between the two scattering classes.[21] To realize this objective, the contrast ratio is maximized, i.e., the maximum contrast ratio is computed in order to obtain the optimal linear weighting vector or optimal polarimetric matched filter. Processing polarimetric synthetic aperture radar (SAR) images with this filter performs a polarization synthesis on the data which yields maximum contrast between classes.

Polarimetric terrain backscatter data observed with satellite and airborne synthetic aperture radars (SAR) have demonstrated potential applications in geologic mapping and terrain cover classification. In previous publications on this subject, Gaussian statistics have been frequently assumed for the radar return signals to build the Bayes terrain classifier. However, abundant experimental evidence shows that terrain radar clutter is non-Gaussian, i.e., non-Rayleigh in amplitude distribution. An n-dimensional anisotropic random walk model is used to derive the zero-mean multivariate K-distribution for polarimetric data.[22] Anisotropy refers to the fact that the polarimetric covariance matrix is not proportional to an identity matrix. In order to apply the K-distribution to the normalized polarimetric classifier problem, the probability density function (PDF) of the normalized K-distributed vector is derived and discussed. Finally, four sets of experimental data, obtained from MIT Lincoln Laboratory, the Jet Propulsion Laboratory (JPL), and the German Aerospace Research Establishment (DLR) of the Federal Republic of Germany, are compared with the K-distribution to lend support to the above model. As compared with C-, L- and P-band polarimetric SAR image simultaneously measured by the Jet Propulsion Laboratory (JPL) on Mt. Shasta, it is found that α appears to decrease from C- to P-band for both the forest and burned areas.

In remote sensing, the encountered geophysical media such as agricultural canopy, forest, snow, or ice are inhomogeneous and contain scatterers in a random manner. Furthermore, weather conditions such as fog, mist, or snow cover can interfere with the electromagnetic observation of the remotely sensed media. In the modeling of such media accounting for the weather effects, a multilayer random medium model has been developed.[23] The scattering effects of the random media are described by three-dimensional correlation functions with variances and correlation lengths corresponding to the fluctuation strengths and the physical geometry of the inhomogeneities, respectively. With proper consideration of the dyadic Green's function and its singularities, the strong fluctuation theory is used to calculate the effective permittivities which account for the modification of the wave speed and attenuation in the presence of the scatterers. The distorted Born approximation is then applied to obtain the correlations of the scattered fields. From the correlation of the scattered field, calculated are the scattering coefficients for polarimetric radar observation or brightness temperature in passive radiometer applications.

The layered random medium model is used to investigate the fully polarimetric scattering of elec-

[21] J.A. Kong, S.H. Yueh, H.H. Lim, R.T. Shin, and J.J. van Zyl, "Classification and Maximum Contrast of Earth Terrain Using Polarimetric Synthetic Aperture Radar Images," In *Progress In Electromagnetics Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 3, Ch. 6, pp. 327-370.

[22] S.H. Yueh, J.A. Kong, R.T. Shin, and H.A. Zebker, "Statistical Modelling for Polarimetric Remote Sensing of Earth Terrain," Tenth International Geoscience and Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990; S.H. Yueh, J.A. Kong, J.K. Jao, R.T. Shin, H.A. Zebker, T. Le Toan, and H. Öttl, "K-distribution and Polarimetric Terrain Radar Clutter," In *Progress In Electromagnetics Research,* ed. J.A. Kong. (New York: Elsevier, 1990), Vol. 3, Ch. 4, pp. 237-275; H.A. Yueh, J.A. Kong, R.T. Shin, H.A. Zebker, and T. Le Toan, "K-distribution and Multi-Frequency Polarimetric Terrain Radar Clutter," *J. Electromag. Waves Appl.,* forthcoming.

[23] S.V. Nghiem, J.A. Kong, and T. Le Toan, "Electromagnetic Wave Modeling for Remote Sensing," International Conference on Directions in Electromagnetic Wave Modeling, New York, October 22-24, 1990; S.V. Nghiem, M. Borgeaud, J.A. Kong, and R.T. Shin, "Polarimetric Remote Sensing of Geophysical Media with Layer Random Medium Model," In *Progress In Electromagnetics Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 3, Ch. 1, pp. 1-73.

tromagnetic waves from vegetation.[24] The vegetation canopy is modeled as an anisotropic random medium containing nonspherical scatterers with preferred alignment. The underlying medium is considered as a homogeneous half space. For a vegetation canopy with low attenuation, the boundary between the vegetation and the underlying medium can give rise to significant coherent effects. The model is used to interpret the measured data for vegetation field such as rice, wheat, or soybean over water or soil. The temporal variation of σ_{hh} and σ_{vv} of the X-band SAR data of rice fields shows a wide range of responses at different growth stages. From the data of wheat, recognizable changes of the angular and polarization behaviour of the backscattering coefficients are observed at X-band before and after the heading of the wheat. For soybean, the data collected during the growing season show similar results for both *h*- and *v*-polarizations. The observed effects on backscattering coefficients of the vegetation structural and moisture conditions at different growth stages can be explained by analyzing the different interaction processes pointed out by the model.

Strong permittivity fluctuation theory is used to solve the problem of scattering from a medium composed of completely randomly oriented scatterers under the low frequency limit.[25] Gaussian statistics are not assumed for the renormalized scattering sources. The effective permittivity is obtained under the low frequency limit and the result is shown to be isotropic due to no preferred direction in the orientation of the scatterers. Numerical results of the effective permittivity are illustrated for oblate and prolate spheroidal scatterers and compared with the results for spherical scatterers. The results derived are shown to be consistent with the discrete scatterer theory. The effective permittivity of random medium embedded with nonspherical scatterers shows a higher imaginary part than that of a spherical scatterer case with equal correlation volume. Under the distorted Born approximation, the polarimetric covariance matrix for the backscattered electric field is calculated for the half-space randomly oriented scatterers. The nonspherical geometry of the scatterers shows significant effects on the cross-polarized backscattering returns σ_{hv} and the correlation coefficient ρ between HH and VV returns. The polarimetric backscattering coefficients can provide useful information in distinguishing the geometry of scatterers.

As an electromagnetic wave propagates through a random scattering medium, such as a forest, its energy is attenuated and random phase fluctuations are induced. The magnitude of the random phase fluctuations induced is important in estimating how well a Synthetic Aperture Radar (SAR) can image objects within the scattering medium. The two-layer random medium model, consisting of a scattering layer between free space and ground, is used to calculate the variance of the phase fluctuations induced between a transmitter located above the random medium and a receiver located below the random medium.[26] The effective permittivity of the random medium is first calculated using the strong fluctuation theory, which accounts for large permittivity fluctuations of the scatterers. The distorted Born approximation is used to calculate the first-order scattered field. A perturbation series for the phase of the received field is then introduced and the variance of the phase fluctuations is solved to first order in the permittivity fluctuations. The variance of the phase fluctuations is also calculated assuming that the transmitter and receiver are in the paraxial limit of the random medium, which allows an analytic solution to be obtained. The effects studied are the dependence of the variance of the phase fluctuations on receiver location in lossy and lossless regions, medium thickness, correlation length and fractional volume of scatterers, depolarization of the incident wave, ground layer permittivity, angle of incidence, and polarization.

In the interpretation of active and passive microwave remote sensing data from earth terrain, the random medium model has been shown to be quite successful. In the random medium model, a correlation function is used to describe the random permittivity fluctuations with associated mean and variance. We calculated the correlation function for a random collection of discrete scatterers imbedded in a background medium of constant permittivity. Correlation functions are first calculated for the simple cases of the uniform distribution of scatterers and the uniform distribution with

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[24] S.V. Nghiem, J.A. Kong, and T. Le Toan, "Application of Layered Random Medium Model to Polarimetric Remote Sensing of Vegetation," URSI International Commission F meeting, Hyannis, Massachusetts, May 16-18, 1990.

[25] H.A. Yueh, R.T. Shin, and J.A. Kong, "Scattering from Randomly Oriented Scatterers with Strong Permittivity Fluctuations," *J. Electromag. Waves Appl. 4(10): 983-1004 (1990).*

[26] N.C. Chu, J.A. Kong, H.A. Yueh, S.V. Nghiem, J.G. Fleischman, S. Ayasli, and R.T. Shin, "Variance of Phase Fluctuations of Waves Propagation through a Random Medium," *J. Electromag. Waves Appl.,* forthcoming.

the hole correction. Then, the correlation function for a more realistic case is obtained using the Percus-Yevik pair distribution function. Once the correlation function is obtained, the strong fluctuation theory is used to calculate the effective permittivities. Then, the distorted Born approximation is used to calculate the backscattering coefficients from a halfspace configuration. The theoretical results are illustrated by comparing the effective permittivities and the backscattering coefficients with the results obtained with the discrete scatterer theory.[27]

The concept of polarimetry in active remote sensing is extended to passive remote sensing. The potential use of the third and fourth Stokes parameters U and V, which play an important role in polarimetric active remote sensing, is demonstrated for passive remote sensing. It is shown that, by the use of the reciprocity principle, the polarimetric parameters of passive remote sensing can be obtained through the solution of the associated direct scattering problem. These ideas are applied to study polarimetric passive remote sensing of periodic surfaces.[28] The solution of the direct scattering problem is obtained by an integral equation formulation which involves evaluation of periodic Green's functions and normal derivative of those on the surface. The study has shown that the brightness temperature of the Stokes parameter *U* can be significant in passive remote sensing. Values as high as 50 K are observed for certain configurations.

Tower-based measurements of sea-state bias were made using a 14 GHz scatterometer (Ku-Bands) and a collocated IR wave gauge during SAXON-CLT. The measured bias was found to be an increasing fraction of the significant wave height with increasing wind speed. The measurements are consistent with a two-scale model of the EM scattering from the ocean surface. The implications of the measurements for the improvement of sea-state bias algorithms are discussed. Results of a more recent series of tower-based measurements in the Gulf of Mexico at both Ku and C bands are presented.[29]

1.2.1 Remote Sensing of Sea Ice

Sponsor

U.S. Navy - Office of Naval Research
Grant N00014-89-J-1107

Project Staff

Professor Jin Au Kong, Dr. Robert T. Shin, Son V. Nghiem

In remote sensing, the encountered geophysical media such as agricultural canopy, forest, snow, or ice are inhomogeneous and contain scatterers in a random manner. Furthermore, weather conditions such as fog, mist, or snow cover can intervene the electromagnetic observation of the remotely sensed media. In the modeling of such media accounting for the weather effects, a multi-layer random medium model has been developed.[30] The scattering effects of the random media are described by three-dimensional correlation functions with variances and correlation lengths corresponding to the fluctuation strengths and the physical geometry of the inhomogeneities, respectively. With proper consideration of the dyadic Green's function and its singularities, the strong fluctuation theory is used to calculate the effective permittivities which account for the modification of the wave speed and attenuation in the presence of the scatterers. The distorted Born approximation is then applied to obtain the correlations of the scattered fields. From the correlation of the scattered field, calculated are the complete set of scattering coefficients for polarimetric radar observation or

[27] H.H. Lim, S.H. Yueh, R.T. Shin, and J.A. Kong, "Correlation Function for a Random Collection of Discrete Scatterers," Tenth International Geoscience and Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990.

[28] M.E. Veysoglu, H.A. Yueh, R.T. Shin and J.A. Kong, "Polarimetric Passive Remote Sensing of Periodic Surfaces," *J. Electromag. Waves Appl.* 5(3): 267-280 (1991).

[29] W.K. Melville, J.A. Kong, R.H. Stewart, W.C. Keller, D. Arnold, A.T. Jessup, and E. Lamarre, "Measurements of Sea-State Bias at Ku and C Bands," URSI International Commission F meeting, Hyannis, Massachusetts, May 16-18, 1990; W.K. Melville, D.V. Arnold, J.A. Kong, A.T. Jessup, E. Lamarre, R.H. Stewart, and W.C. Keller, "Measurements of EM Bias at Ku and C Bands," OCEANS'90, Washington, D.C., September 24-26, 1990.

[30] S.V. Nghiem, J.A. Kong, and T. Le Toan, "Electromagnetic Wave Modeling for Remote Sensing," International Conference on Directions in Electromagnetic Wave Modeling, New York, October 22-24, 1990; S.V. Nghiem, M. Borgeaud, J.A. Kong, and R.T. Shin, "Polarimetric Remote Sensing of Geophysical Media with Layer Random Medium Model," In *Progress In Electromagnetics Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 3, Ch. 1, pp. 1-73.

brightness temperature in passive radiometer applications.

Fully polarimetric scattering of electromagnetic waves from snow and sea ice is studied with a layered random medium model and applied to interpret experimental data obtained under laboratory controlled conditions.[31] There is considerable interest in identifying and classifying ice types by using polarimetric scattering data. Due to differences in structure and composition, ice of different types such as frazil, first-year, or multiyear can have different polarimetric scattering behaviors. To study the polarimetric response of sea ice, the layered random medium model is used.[32] In this model, the sea-ice layer is described as an anisotropic random medium composed of a host medium with randomly embedded inhomogeneities, such as elongated brine inclusions, which can have preferred orientation direction. The underlying sea-water layer is considered as a homogenous half space. The scattering effect of the inhomogeneities in the sea ice are characterized by three-dimensional correlation function with variance and correlation lengths respectively corresponding to the fluctuation strength and the physical geometry of the scatterers. The effective permittivity of the sea ice is calculated with the strong fluctuation theory and the polarimetric backscattering coefficients are obtained under the distorted Born approximation. The distinction on the characteristics of different ice types are investigated with the conventional backscattering coefficients and the complex correlation coefficient ρ between σ_{hh} and σ_{vv}. The correlation coefficient ρ contains additional information on the sea-ice structure and can be useful in the identification of the ice types. By relating to the covariance matrices, the model is used to explain the polarization signatures of different ice types. In the case of snow-covered sea ice, the snow layer is modeled as an isotropic random medium and the obtained solution accounts for the effect of snow cover on polarimetric scattering properties of sea ice.

To explain polarimetric scattering from the experimentally simulated bare sea ice, the two-layer configuration is used to model sea-ice layer over sea water. The distinction on the characteristics of the media are investigated with the conventional backscattering coefficients and the complex correlation coefficient ρ between σ_{hh} and σ_{vv}. For ice-type identification, the measured covariance matrices are studied with the model to infer the physical characteristics pertaining to the different ice types. The three-layer configuration is then used to investigate the effects on fully polarimetric radar returns from snow covered sea ice.

Accurate calibration of polarimetric radar systems is essential for the polarimetric remote sensing of earth terrain. A polarimetric calibration algorithm using three arbitrary in-scene reflectors is developed.[33] The transmitting and receiving ports of the polarimetric radar are modeled by two unknown polarization transfer matrices. These unknown matrices are determined using the measured scattering matrices from the calibration targets. A Polarization-Basis Transformation technique is introduced to convert the scattering matrices of the calibration targets into one of the six sets of targets with simpler scattering matrices. Then, the solution to the original problem can be expressed in terms of the solution obtained using the simpler scattering matrices. The uniqueness of polarimetric calibration using three targets is addressed for all possible combinations of calibration targets. The effect of misalignment of the calibration targets and the sensitivity of the polarimetric calibration algorithm to the noise are illustrated by investigating several sets of calibration targets in detail.

Strong permittivity fluctuation theory is used to solve the problem of scattering from a medium composed of completely randomly oriented scat-

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[31] S.V. Nghiem, J.A. Kong, R.T. Shin, H.A. Yueh, and R. Onstott, "Theoretical Models and Experimental Measurements for Polarimetric Remote Sensing of Snow and Sea Ice," URSI International Commission F meeting, Hyannis, Massachusetts, May 16-18, 1990.

[32] S.V. Nghiem, J.A. Kong, and R.T. Shin, "Study of Polarimetric Response of Sea Ice with Layered Random Medium Model," Tenth International Geoscience & Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990.

[33] S.H. Yueh, J.A. Kong, and R.T. Shin, "Calibration of Polarimetric Radars using In-Scene Reflectors," In *Progress In Electromagnetic Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 3, Ch. 9, pp. 451-510; S.H. Yueh, J.A. Kong, and R.T. Shin, "Calibration of Polarimetric Radars Using In-Scene Reflectors," Tenth International Geoscience and Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990.

terers under the low frequency limit.[34] Gaussian statistics is not assumed for the renormalized scattering sources. The effective permittivity is obtained under the low frequency limit and the result is shown to be isotropic due to no preferred direction in the orientation of the scatterers. Numerical results of the effective permittivity are illustrated for oblate and prolate spheroidal scatterers and compared with the results for spherical scatterers. The results derived are shown to be consistent with the discrete scatterer theory. The effective permittivity of random medium embedded with nonspherical scatterers shows a higher imaginary part than that of spherical scatterer case with equal correlation volume. Under the distorted Born approximation, the polarimetric covariance matrix for the backscattered electric field is calculated for the half-space randomly oriented scatterers. The nonspherical geometry of the scatterers shows significant effects on the cross-polarized backscattering returns σ_{hv} and the correlation coefficient ρ between HH and VV returns. The polarimetric backscattering coefficients can provide useful information in distinguishing the geometry of scatterers.

In the interpretation of active and passive microwave remote sensing data from earth terrain, the random medium model has been shown to be quite successful. In the random medium model, a correlation function is used to describe the random permittivity fluctuations with associated mean and variance. In the past, the correlation functions used were either assumed to be of certain form or calculated from cross sectional pictures of scattering media. We calculated the correlation function for a random collection of discrete scatterers imbedded in a background medium of constant permittivity. Correlation functions are first calculated for the simple cases of the uniform distribution of scatterers and the uniform distribution with the hole correction. Then, the correlation function for a more realistic case is obtained using the Percus-Yevik pair distribution function. Once the correlation function is obtained, the strong fluctuation theory is used to calculate the effective permittivities. Then, the distorted Born approximation is used to calculate the backscattering coefficients from a halfspace configuration. The theoretical results are illustrated by comparing the effective permittivities and the backscattering coefficients with the results obtained with the discrete scatterer theory.[35]

1.3 SAR Image Interpretation and Simulation

Sponsors

National Aeronautics and Space Administration
Grant NAGW-1272 and Agreement 958461
U.S. Army - Corps of Engineers
Contract DACA39-87-K-0022

Project Staff

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Classification or identification of radar targets from measurements of their radar signatures continues to be an area of considerable interest and active research. In the past, a variety of classification algorithms have been proposed, and these techniques have yielded varied levels of effectiveness in differing applications. One novel group of classification techniques which overcome the limitations of the conventional ones, and which has recently received considerable attention, is a set of methods based on the use of neural networks. As classifiers, neural networks have shown greater flexibility than conventional algorithms, adapting themselves more easily to distributions possessing a high degree of complexity, and have found application in diverse problems such as speech recognition and multisensor fusion. Presented a set of sample feature vectors during the training process, the neural network tries to selectively and automatically choose those characteristics of the feature vector which lead to the greatest separability between classes. The application of neural networks to the problem of target classification from high range resolution profiles is considered.[36] The effectiveness of the neural network classifier is demonstrated using synthetically generated range profiles of two groups of geometries,

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[34] H.A. Yueh, R.T. Shin, and J.A. Kong, "Scattering from Randomly Oriented Scatterers with Strong Permittivity Fluctuations," *J. Electromag. Waves Appl. 4(10): 983-1004 (1990).*

[35] H.H. Lim, S.H. Yueh, R.T. Shin, and J.A. Kong, "Correlation Function for a Random Collection of Discrete Scatterers," Tenth International Geoscience and Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990.

[36] Atkins, R.G., R.T. Shin, and J.A. Kong. "A Neural Net Method for High Range Resolution Target Classification," In *Progress In Electromagnetics Research,* ed. J.A. Kong. (New York: Elsevier, 1990), Vol. 4, Ch. 7, pp. 255-292.

produced using RCS prediction techniques. For both groups, the neural network approach is compared with the conventional techniques of profile matching, and Euclidean and Mahalanobis distance classifiers. In addition, the performance of both conventional and neural network classifiers in the presence of additive noise and alignment uncertainty is explored. Finally, a comparison of the computational and storage requirements of each approach is presented.

Besides classifying earth terrain into different classes, there is also considerable interest in determining the optimal polarizations that maximize contrast between two scattering classes in polarimetric radar images. Contrast enhancement is a processing technique which modifies the input data structure so that either the human observer, computer, or other hardware devices can extract certain information from the processed data more readily after the change. The polarimetric properties of the radar returns are utilized to enhance the contrast between two scattering classes. It is assumed a priori that complete statistical knowledge of the two scattering classes or types exists and the polarimetric signals backscattered from the two scattering classes are independent. The processing requirement is then to determine the optimal transmitting and receiving polarization state which will maximize the separation of the average power returns between the two classes. Applying such a technique to radar imagery allows for better discrimination of the two classes.[37]

An n-dimensional anisotropic random walk model is used to derive the zero-mean multivariate K-distribution for polarimetric data.[38] Anisotropy refers to the fact that the polarimetric covariance matrix is not proportional to an identity matrix. The polarimetric amplitude data are normalized by the square root of the illuminated area so that the measured covariances of the polarimetric data are in terms of scattering cross section per unit area. The polarimetric covariance matrix is shown to be directly related to that of a single scatterer. The result is then generalized to the nonzero-mean multivariate K-distribution. There are two ways to introduce nonzero mean into the K-distribution. The directional bias random walk model will lead to a generalized K-distribution, and the homodyned approach will result in a homodyned K-distribution. We applied both approaches in deriving the nonzero mean K-distribution and discussed the corresponding scattering processes. In order to apply the K-distribution to the normalized polarimetric classifier problem, the probability density function (PDF) of the normalized K-distributed vector is derived and discussed. Finally, four sets of experimental data, obtained from MIT Lincoln Laboratory, the Jet Propulsion Laboratory (JPL), and the German Aerospace Research Establishment (DLR) of the Federal Republic of Germany, are compared with the K-distribution to lend support to the above model. As compared with C-, L- and P-band polarimetric SAR image simultaneously measured by the Jet Propulsion Laboratory (JPL) on Mt. Shasta, it is found that α appears to decrease from C- to P-band for both the forest and burned areas.

In remote sensing, the encountered geophysical media such as agricultural canopy, forest, snow, or ice are inhomogeneous and contain scatterers in a random manner. Furthermore, weather conditions such as fog, mist, or snow cover can intervene the electromagnetic observation of the remotely sensed media. In the modeling of such media accounting for the weather effects, a multi-layer random medium model has been developed.[39] The scattering effects of the random media are described by three-dimensional correlation functions with variances and correlation lengths corresponding to the fluctuation strengths and the physical geometry of the inhomogeneities, respectively. With proper consideration of the dyadic Green's function and its singularities, the strong

37 J.A. Kong, S.H. Yueh, H.H. Lim, R.T. Shin, and J.J. van Zyl, "Classification and Maximum Contrast of Earth Terrain Using Polarimetric Synthetic Aperture Radar Images," In *Progress In Electromagnetics Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 3, Ch. 6, pp. 327-370.

38 S.H. Yueh, J.A. Kong, R.T. Shin, and H.A. Zebker, "Statistical Modelling for Polarimetric Remote Sensing of Earth Terrain," Tenth International Geoscience and Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990; S.H. Yueh, J.A. Kong, J.K. Jao, R.T. Shin, H.A. Zebker, T. Le Toan, and H. Öttl, "K-distribution and Polarimetric Terrain Radar Clutter," In *Progress In Electromagnetics Research,* ed. J.A. Kong. (New York: Elsevier, 1990), Vol. 3, Ch. 4, pp. 237-275; H.A. Yueh, J.A. Kong, R.T. Shin, H.A. Zebker, and T. Le Toan, "K-distribution and Multi-Frequency Polarimetric Terrain Radar Clutter," *J. Electromag. Waves Appl.,* forthcoming.

39 S.V. Nghiem, J.A. Kong, and T. Le Toan, "Electromagnetic Wave Modeling for Remote Sensing," International Conference on Directions in Electromagnetic Wave Modeling, New York, October 22-24, 1990; S.V. Nghiem, M. Borgeaud, J.A. Kong, and R.T. Shin, "Polarimetric Remote Sensing of Geophysical Media with Layer Random Medium Model," In *Progress In Electromagnetics Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 3, Ch. 1, pp. 1-73.

fluctuation theory is used to calculate the effective permittivities which account for the modification of the wave speed and attenuation in the presence of the scatterers. The distorted Born approximation is then applied to obtain the correlations of the scattered fields. From the correlation of the scattered field, the complete set of scattering coefficients for polarimetric radar observation or brightness temperature in passive radiometer applications are calculated.

Fully polarimetric scattering of electromagnetic waves from snow and sea ice is studied with a layered random medium model and applied to interpret experimental data obtained under laboratory controlled conditions.[40]

Strong permittivity fluctuation theory is used to solve the problem of scattering from a medium composed of completely randomly oriented scatterers under the low frequency limit.[41] Gaussian statistics is not assumed for the renormalized scattering sources. The effective permittivity is obtained under the low frequency limit and the result is shown to be isotropic due to no preferred direction in the orientation of the scatterers. Numerical results of the effective permittivity are illustrated for oblate and prolate spheroidal scatterers and compared with the results for spherical scatterers. The results derived are shown to be consistent with the discrete scatterer theory. Under the distorted Born approximation, the polarimetric covariance matrix for the backscattered electric field is calculated for the half-space randomly oriented scatterers. The nonspherical geometry of the scatterers shows significant effects on the cross-polarized backscattering returns σ_{hv} and the correlation coefficient ρ between HH and VV returns. The polarimetric backscattering coefficients can provide useful information in distinguishing the geometry of scatterers.

The layered random medium model is used to investigate the fully polarimetric scattering of electromagnetic waves from vegetation.[42] The vegetation canopy is modeled as an anisotropic random medium containing nonspherical scatterers with preferred alignment. The underlying medium is considered as a homogeneous half space. The scattering effect of the vegetation canopy are characterized by three-dimensional correlation functions with variances and correlation lengths respectively corresponding to the fluctuation strengths and the physical geometries of the scatterers.

The model is used to interpret the measured data for fields of vegetation such as rice, wheat, or soybean over water or soil. The temporal variation of σ_{hh} and σ_{vv} of the X-band SAR data of rice fields shows a wide range of responses at different growth stages. From the data of wheat, recognizable changes of the angular and polarization behaviour of the backscattering coefficients are observed at X-band before and after the heading of the wheat. For soybean, the data collected during the growing season shows similar results for both *h*- and *v*-polarizations. The observed effects on backscattering coefficients of the vegetation structural and moisture conditions at different growth stages can be explained by analyzing the different interaction processes pointed out by the model.

In the interpretation of active and passive microwave remote sensing data from earth terrain, the random medium model has been shown to be quite successful. In the random medium model, a correlation function is used to describe the random permittivity fluctuations with associated mean and variance. In the past, the correlation functions used were either assumed to be of certain form or calculated from cross-sectional pictures of scattering media. We calculated the correlation function for a random collection of discrete scatterers imbedded in a background medium of constant permittivity. Correlation functions are first calculated for the simple cases of the uniform distribution of scatterers and the uniform distribution with the hole correction. Then, the correlation function for a more realistic case is obtained using the Percus-Yevik pair distribution function. Once the correlation function is obtained, the strong fluctuation theory is used to calculate the effective permittivities. Then, the distorted Born approximation is used to calculate the backscattering coefficients from a halfspace configuration. The theoretical results are illustrated by comparing the effective permittivities and the backscattering coef-

[40] S.V. Nghiem, J.A. Kong, R.T. Shin, H.A. Yueh, and R. Onstott, "Theoretical Models and Experimental Measurements for Polarimetric Remote Sensing of Snow and Sea Ice," URSI International Commission F meeting, Hyannis, Massachusetts, May 16-18, 1990.

[41] H.A. Yueh, R.T. Shin, and J.A. Kong, "Scattering from Randomly Oriented Scatterers with Strong Permittivity Fluctuations," *J. Electromag. Waves Appl. 4(10): 983-1004 (1990).*

[42] S.V. Nghiem, J.A. Kong, and T. Le Toan, "Application of Layered Random Medium Model to Polarimetric Remote Sensing of Vegetation," URSI International Commission F meeting, Hyannis, Massachusetts, May 16-18, 1990.

ficients with the results obtained with the discrete scatterer theory.[43]

As an electromagnetic wave propagates through a random scattering medium, such as a forest, its energy is attenuated and random phase fluctuations are induced. The magnitude of the random phase fluctuations induced is important in estimating how well a Synthetic Aperture Radar (SAR) can image objects within the scattering medium. The two-layer random medium model, consisting of a scattering layer between free space and ground, is used to calculate the variance of the phase fluctuations induced between a transmitter located above the random medium and a receiver located below the random medium.[26] The scattering properties of the random medium are characterized by a correlation function of the random permittivity fluctuations. The effective permittivity of the random medium is first calculated using the strong fluctuation theory, which accounts for large permittivity fluctuations of the scatterers. The distorted Born approximation is used to calculate the first-order scattered field. A perturbation series for the phase of the received field is then introduced and the variance of the phase fluctuations is solved to first order in the permittivity fluctuations. The variance of the phase fluctuations is also calculated assuming that the transmitter and receiver are in the paraxial limit of the random medium, which allows an analytic solution to be obtained. The effects studied are the dependence of the variance of the phase fluctuations on receiver location in lossy and lossless regions, medium thickness, correlation length and fractional volume of scatterers, depolarization of the incident wave, ground layer permittivity, angle of incidence, and polarization.

Classification of earth terrain within an image is one of the many important applications of polarimetric data. Both the supervised and unsupervised classification techniques are applied to San Francisco Bay and Traverse City Synthetic Aperture Radar (SAR) images, supplied by the Jet Propulsion Laboratory.[44] These images were collected at L-band (1.225 GHz) with near range along the upper part of the image. There are 896 pixels in the range and 4096 pixels in the azimuth with approximately 10 m by 3 m resolution per pixel. For supervised classification processing, the Bayes technique is used to classify fully polarimetric and normalized polarimetric SAR data. An unsupervised technique, based on comparing general properties of the Stokes parameters of the scattered wave to that of simple scattering models, is also discussed. It is shown that supervised classification yields the best overall performance when accurate classifier training data are used, whereas unsupervised classification is applicable when training data are not available.

1.4 Microwave and Millimeter Wave Integrated Circuits

Sponsors

U.S. Air Force - Electronic Systems Division
Contract F19628-88-K-0013
U.S. Navy - Office of Naval Research
Grant N00014-89-J-1019

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Frequency domain analytical work with complicated microstrip circuits has generally been done using planar circuit concepts in which the substrate is assumed to be thin enough that propagation can be considered in two dimensions by surrounding the microstrip with magnetic walls. Fringing fields are accounted for by using either static or dynamic effective dimensions and permittivities. Limitations of these methods are that fringing, coupling, and radiation must all be handled empirically since they are not allowed for in the model. Also, the accuracy is questionable when the substrate becomes thick relative to the width of the microstrip. To fully account for these effects, it is necessary to use a full-wave solution.

Finite difference time domain methods have recently been used to effectively calculate the frequency dependent characteristics of microstrip discontinuities. Analysis of the fundamental discontinuities is of great importance since more complicated circuits can be realized by intercon-

[43] H.H. Lim, S.H. Yueh, R.T. Shin, and J.A. Kong, "Correlation Function for a Random Collection of Discrete Scatterers," Tenth International Geoscience and Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990.

[44] J.A. Kong, S.H. Yueh, H.H. Lim, R.T. Shin, and J.J. van Zyl, "Classification and Maximum Contrast of Earth Terrain Using Polarimetric Synthetic Aperture Radar Images," In *Progress In Electromagnetics Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 3, Ch. 6, pp. 327-370.

necting microstrip lines with these discontinuities and using transmission line and network theory. Some circuits, however, such as patch antennas, may not be realized in this way. Additionally, if the discontinuities are too close to each other the use of network concepts will not be accurate due to the interaction of evanescent waves. To accurately analyze these types of structures it is necessary to simulate the entire structure in one computation. The finite difference time domain (FDTD) method shows great promise in its flexibility to handle a variety of circuit configurations. An additional benefit of the time domain analysis is that a broadband pulse may be used as the excitation and the frequency domain parameters may be calculated over the entire frequency range of interest by Fourier Transform of the transient results.

The frequency dependent scattering parameters are calculated for several printed microstrip circuits, specifically, a line-fed rectangular patch antenna, a low pass filter, and a rectangular branch line coupler.[45] These circuits represent resonant microstrip structures on an open substrate, hence, radiation effects can be significant, especially for the microstrip antenna. Calculated results are presented and compared with experimental measurements.

For microwave integrated circuit applications, the characteristics of interconnects have been investigated for propagation modes, time response, crosstalk, coupling, delay, etc. In these analyses, it is assumed that quasi-TEM modes are guided along the multiconductor transmission line. 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. However, the infinite extent of the structure was incorporated, but only a two-layer medium was considered.

A quasi-TEM analysis of coupled lossy microstrip lines of finite strip thickness embedded in different layers of a lossy isotropic stratified medium is presented.[46] First, a spectral domain scalar Green's function in a lossy isotropic stratified medium is derived. Based on the scalar Green's function, a set of coupled integral equations is obtained for the charge distribution on the strip surfaces. The method of moments is then applied where 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 problem 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 line, 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.

A full modal analysis is used to study the dispersion characteristics of microstrip lines periodically loaded with crossing strips in a stratified uniaxially anisotropic medium.[47] 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.

The excitation of the earth-ionosphere waveguide by point dipoles at satellite heights was studied by Einaudi and Wait. In their formulation, the ionosphere was crudely modeled as a single D-layer, moreover the geomagnetic field was assumed to be vertical, thus rendering the validity of the model to polar regions. Then, a more general analysis was performed where the

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[45] D.M. Sheen, S.M. Ali, M.D. Abouzahra, and J.A. Kong, "Application of the Three Dimensional Finite Difference Time-Domain Method to the Analysis of the Planar Microstrip Circuits," *IEEE Trans. Microwave Theory Tech.* 38(7): 849-857 (1990).

[46] J.F. Kiang, S.M. Ali, and J.A. Kong, "Modelling of Lossy Microstrip Lines with Fine Thickness," *Progress In Electromagnetics Research,* ed. J.A. Kong (New York: Elsevier, 1990), Vol. 4, Ch. 3, pp. 85-117.

[47] C.W. Lam, S.M. Ali, and J.A. Kong, "The Propagation Characteristics of Signal Lines with Crossing Strips in Multilayered Anisotropic Media," *J. Electromag. Waves Appl.* 4(10): 1005-1021 (1990).

geomagnetic field was assumed to be arbitrarily-oriented and the earth to be curved along the direction of propagation. However, the ionosphere was assumed to be a semi-infinite homogeneous medium and the results presented in these papers were limited to a frequency of 75 Hz. Furthermore, in these papers, an indirect scheme was employed to formulate the response of point dipole sources: the case of line quadrupole sources was first considered and then at the end of the development, the results were converted to apply to a point source.

We presented a rigorous approach to the problem of radiation of electric or magnetic sources in a stratified arbitrary magnetized linear plasma.[12] The fields are obtained in terms of dyadic Green's functions of electric or magnetic type represented in the spectral domain. First, the dyadic Green's function for an unbounded arbitrary magnetized linear plasma is derived. The formulation is considerably simplified by using the kDB system of coordinates in conjunction with the Fourier transform. This leads to compact and explicit expressions for the dyadic Green's functions. The distributional singular behavior of the various dyadic Green's functions in the source region is investigated and taken into account by extracting the delta function singularities. Finally, the dyadic Green's function in any arbitrary layer is obtained in terms of appropriately defined global upward and downward reflection and transmission matrices. The field expressions for an arbitrary distribution of sources or linear antennas can be obtained by performing a convolution integral over the volume of the antenna weighted by the current density on the antenna.

The integral equation method has been used to solve for the dispersion relation of the rectangular dielectric waveguide.[48] This method incorporates the continuous spectrum, and hence the radiation loss is taken into account. However, no results concerning practical single and coupled dielectric strip waveguides were presented; and the leakage phenomenon was not investigated. We derived an integral equation formulation using the dyadic Green's function 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. The integral equation formulation for an arbitrary number of inhomogeneous dielectric strips is derived and Galerkin's method is used to obtain the matrix eigenvalue equations. Numerical results and discussions are presented.

Cylindrical microstrip antennas have many applications in high-speed aircraft and spacecraft because of their conformity with the aerodynamical structure of such vehicles. Recently, there has been some progress in the theoretical study of this kinds of antenna. The radiation from the wraparound cylindrical microstrip element was computed using a magnetic wall cavity model. More recently, the radiation from the wraparound and the rectangular patches was computed by assuming an electric surface current distribution on the microstrip patch. The excitation problem of realizing such a current distribution was not addressed in these investigations. Furthermore, the input impedance for the cylindrical microstrip antennas was not reported.

We addressed the more realistic problem of the radiation from a cylindrical microstrip antenna excited by a probe.[49] Both the cylindrical-rectangular and the wraparound elements are discussed. The current distribution on the patch is rigorously formulated using a cylindrically stratified medium approach. A set of vector integral equations is derived which governs the current distribution on the patch. This set of equations is then solved using a moment method in which the patch current is expanded in terms of a complete set of basis functions that can take into account the edge singularity condition. The input impedance together with the radiation pattern are derived both exactly and in the small substrate thickness limit where a single mode approximation is employed.

A microstrip antenna consisting of two circular microstrip disks in a stacked configuration driven by coaxial probe excitation is considered.[50] 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

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[48] J.F. Kiang, S.M. Ali, and J.A. Kong, "Integral Equation Solution to the Guidance and Leakage Properties of Coupled Dielectric Strip Waveguides," *IEEE Trans. Microwave Theory Tech.* 38(2): 193-203 (1990).

[49] T.M. Habashy, S.M. Ali, and J.A. Kong, "Input Impedance Parameters and Radiation Pattern of Cylinderical-Rectangular and Wraparound Microstrip Antennas," *IEEE Trans. Antennas Propag.* 38(5): 722-731 (1990).

[50] A.N. Tulintseff, S.M. Ali, and J.A. Kong, "Input Impedance of a Probe-Fed Stacked Circular Microstrip Antenna," *IEEE Trans. Antennas Propag.,* forthcoming.

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 is 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.

The study of electromagnetic radiation from sources in the ionospheric plasmas has received much attention in the research on the satellite-borne antennas. For many years, special attention has been given to the radiation in the very low frequency (VLF) band due to its applications in the down-link communication systems. Intensive efforts had been placed on the investigation on the single element radiations by many authors, both theoretically and experimentally. However, limited by its low radiation efficiency, the utility of a practically sized single VLF radiator could depend upon the focusing effects characterized by the inflection points on the k-surface associated with the medium. In recent years, the construction of a large space-based antenna array has been made feasible by the progress of spacecraft technology. With a properly phased large VLF linear or planar array, a narrow beam width and consequently the high directivity can then be achieved.

The far field pattern of a VLF phased array located in a magnetized plasma is studied. The general principles of antenna array design in the anisotropic media are discussed.[51] Special attention is drawn to the two-dimension planar array allowed to rotate with respect to an axis perpendicular to the plane of the array, and the main beam of which is kept in the same direction as that of the geomagnetic field line during the rotation. The applicability of the principle of pattern multiplication as well as the effects of different types of radiating elements for different k-surface geometries are investigated.

There has been considerable interest in the theoretical study of scattering from chiral media. Chiral medium characterized by biisotropic constitutive relation is a special case of the bianisotropic medium whose electromagnetic properties have been extensively studied by Kong. Periodic gratings have been the object of extensive research through the years because of their many applications in distributed feedback lasers, integrated optics, acousto-optics, quantum electronics, and holography. For the analysis of wave diffraction by periodic surface grating, methods, including the method of moments and extended boundary condition method, are rigorous and in general computationally efficient. For the analysis of periodic slanted dielectric gratings, a coupled-wave method has been developed.

The coupled-wave theory is generalized to analyze the diffraction of waves by chiral gratings for arbitrary angle of incidence and polarizations.[52] 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.

1.5 High-Speed Integrated Circuit Interconnects

Sponsors

Digital Equipment Corporation
IBM Corporation

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[51] C.H. Han, J.A. Kong, T.M. Habashy, and M.D. Grossi, "Principles of VLF Antenna Array Design in Magnetized Plasmas," URSI National Radio Science Meeting, Boulder, Colorado, January 3-5, 1990.

[52] S.H. Yueh and J.A. Kong, "Analysis of Diffraction from Chiral Gratings," *J. Electromag. Waves Appl.*, forthcoming.

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We presented, a new hybrid cross-section finite element/coupled integral equationbreak method,[53] 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.

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 matrice 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 skin depth, we 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 is the average cross-section of the conductors, and δ is the skin depth.

1.6 ILS/MLS Frequency Management Assessment

Sponsor

U.S. Department of Transportation
Contract DTRS-57-88-C-00078

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The Instrument Landing System (ILS) for airport runway was developed during World War II and was standardized by the end of the war. It is a low-approach guidance system to aid pilots in landing the aircraft when weather is bad and visibility is poor. ILS is currently used worldwide as the standard precision approach guidance system. It consists of three basic components: a localizer to line the airplane up with the runway, a glideslope for vertical glide path control, and marker beacons for homing and position determination. To improve the range accuracy, Distance Measurement Equipment (DME) is often used as a replacement for the marker beacon in newer ILS.

[53] M.J. Tsuk and J.A. Kong, "A Hybrid Method for the Calculation of the Resistance and Inductance of Transmission Lines with Arbrary Cross-Sections," submitted to *IEEE Trans. Microwave Theory Tech.*

The localizer transmitter is installed approximately 1000 feet from the end of the runway. The glide slope transmitter is located on a line perpendicular to the runway centerline at the point where airplanes touch down.

The ILS localizer operates in the band 108.00 to 112.00 MHz using only those frequencies where the digit in the tenths-of-a-megahertz position is odd. Prior to the late 1970s, there were 20 channels allocated for localizer at 100 kHz spacing (108.1 MHz, 108.3 MHz, etc.). However, with the rapid increase of air traffic, 20 ILS localizer channels were insufficient to meet the demand. In order to solve this problem, the separation between localizer channels was reduced to 50 kHz from 100 kHz. Although the number of channels allocated for the localizer was thus increased to 40 (108.1 MHz, 108.15 MHz, 108.3 MHz, 108.35 MHz, etc.), not all new channel frequencies are assigned because some older localizer receivers designed in accordance with RTCA DO-131 (100 KHz channel spacing) are still in use today and may not operate properly in the environment in which the separation between localizer channels is 50 kHz.

Microwave landing system (MLS) was developed to overcome some of the problems and limitations associated with the instrument landing system (ILS). In order to install ILS, flat terrain over an extended area is required since glideslope antennas use ground reflection to generate desired radiation patterns. Furthermore, clearance requirement around an ILS site is very stringent to avoid guidance error caused by multipath interference. MLS overcomes these limitations by using much higher frequencies (5030 MHz - 5090 MHz) so that very narrow beams can be formed from antennas of reasonable sizes. The narrow beams can avoid most structures near the airport and flat terrain is not required in front of the vertical guidance part of MLS. Current ILS also confines arriving aircrafts to a single straight approach path. The long straight approach paths could create some traffic problems in multiairport environments. Since MLS allows curved approach paths, the aircrafts are allowed to make shorter direct approaches. This is very desirable for fuel conservation and noise reduction. Another advantage is that the number of channels available for MLS is five times that for ILS. There are 200 channels allocated for MLS in the band between 5030 MHz and 5090 MHz. This allows installation of more MLS facilities in areas of heavy air traffic without interference problems. The MLS currently being deployed is called a time-reference scanning-beam (TRSB) system.

In view of the ILS frequency congestion problems that metropolitan areas throughout the continental United States are facing and for future planning with MLS growth, the objectives of this project are to utilize specially developed computer simulation tools named EMSALS (Electromagnetic Simulations Applied to Landing Systems) for both ILS and MLS to:

1. predict channel capacities of ILS and MLS in congested metropolitan areas, such as New York, Chicago, Los Angeles and Dallas/Fort Worth as well as in any other geographical area,
2. perform quantitative analyses of in-band (aviation band) and out-of-band electromagnetic interferences, and
3. make quantitative assessments of electromagnetic interferences within the ILS/MLS service volume.

Based upon the above requirements, we established methodology for implementing the simulation software from theoretical studies of electromagnetic interference phenomena. In brief, we first locate potential interference sources and use electromagnetic propagation model to compute the desired and interfering signal strengths. Then interference analysis based upon safety standard, which is developed from the receiver model, is performed. Finally, interference analysis results for various locations are combined to make channel capacity assessment. Accordingly, the following tasks have been carried out:

1. identification of radiation sources, including in-band and out-of-band sources,
2. development of propagation models, to be used to calculate the interference level,
3. development of receiver models, to determine the quantitative effect of interference signals,
4. verification and validation of models through testing and checking against existing data,
5. development of graphical user interface which allows for interactive retrieval of quantitative information on assessment.

In this project, we have utilized computer simulation tool EMSALS to analyze the frequency congestion and electromagnetic interference problems for the continental United States, with emphasis in ten mutually-disjointed complex metropolitan areas. Each of them is formed by drawing 100-nmi circles around a few central locations. The central locations of different areas are typically more than 200 nmi away, so they can be considered to be independent for interference assessment. These areas are:

1. New York-Philadelphia-D.C.
2. Chicago
3. Miami-Tampa-Orlando
4. Dallas-Ft. Worth-Houston
5. Los Angeles-San Diego
6. San Francisco
7. Denver
8. Detroit
9. Memphis-Nashville-Atlanta
10. St. Louis-Kansas City

The results of computer simulation across the ten regions predict significant shortfall in ILS channel capacity. For example, ILS substantially fails to meet the precision landing runway requirements in the New York-Philadelphia-DC area. The limitation of ILS spectrum is best illustrated by the fact that as frequency assignment priorities are changed, the number of available channels for specific regions in a large geographical area will vary because assigning more frequencies in one region can seriously reduce the channel availability in nearby regions. In other areas such as Denver and Chicago, we demonstrated that the limited ILS channel capacity could potentially impede the expansion plans.

1.7 Superconducting Electronics

Sponsor

Defence Advanced Research Projects Agency
Contract MDA972-90-C-0021

Project Staff

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The calculation of the electrical parameters of superconducting transmission lines is very important not only for design of circuitry and devices, but also for the characterization of the superconductors. Currently, there is considerable effort directed at microwave-frequency characterization of both high-T_c and low-T_c superconducting thin films. The microwave measurements can determine the fundamental physical properties of these films, such as penetration depth, intrinsic surface resistance or the real part of the conductivity, as well as other parameters such as critical temperature, critical current density, critical magnetic field strength, etc. To enable measurement at microwave frequencies, these films are often fabricated into stripline or microstrip resonators. The resonant frequencies and the associated quality factors are readily measured as a function of temperature. To accurately infer the fundamental physical properties from these measurements requires accurate calculation of the current distribution, resistance, and inductance of the stripline.

We presented a method for the calculation of the current distribution, resistance, and inductance, as functions of the penetration depth for a superconducting strip transmission line.[54] Unlike the previous work, resistance will be considered in the formulation as well as inductance. The inductance calculation is then used to determine the penetration depth at zero temperature, $\lambda(0)$, for *Nb*, *NbN*, and $YBa_2Cu_3O_{7-x}$ superconducting thin films from the measured temperature dependence of the resonant frequency of a stripline resonator. The calculations are also used to convert measured temperature dependence of the stripline resonator Q to the intrinsic surface resistance as a function of temperature for the *Nb* resonator. Agreement between the intrinsic surface resistance of *Nb* determined in this way and the BCS theory calculation is shown.

Among the most promising applications of high-T_c superconductors in computers is in passive elements, such as interconnects, signal transmission lines, or board level wiring. The signal delay in a computing system can be reduced by increasing the density of circuits. The finer dimensions of the interconnecting lines can cause unacceptable signal losses in normal metals due to resistive attenuation. However, superconductors offer lower attenuation and signal distortion.

Approximate theoretical analyses and experiments have been performed to study the propagation characteristics of high-T_c superconducting planar transmission lines. However, no rigorous analysis of the wave propagation in the superconducting microstrip lines has been performed. A full-wave analysis has only been applied to the special case when the film thickness is thin compared to the penetration depth of the superconductor and thus surface impedance boundary condition can be used. Also, in the previous studies, no information

[54] D.M. Sheen, S.M. Ali, D.E. Oates, R.S. Whers, and J.A. Kong, "Current Distribution, Resistance, and Inductance for Superconducting Strip Transmission Lines," *IEEE Trans. Appl. Superconductivity,* forthcoming.

on the current distribution in the strips has been presented.

We are investigating a hybrid-mode analysis of superconducting planar transmission lines with finite film thickness.[55] Two different geometries are considered: the microstrip and the coplanar strips. The cross sections of the strips are assumed to be rectangular. Using the dyadic Green's function, the problem is formulated in terms of a set of integral equations. Galerkin's method is then used to solve the integral equations for the dispersion relation. The propagation and attenuation constants are obtained as function of frequency for different physical and geometrical parameters of the superconducting lines. The current density distribution in the strips is calculated for various penetration depths and film thicknesses.

1.8 Publications and Conference Papers

Atkins, R.G., R.T. Shin, and J.A. Kong. "A Neural Net Method for High Range Resolution Target Classification." In *Progress In Electromagnetics Research.* Ed. J.A. Kong. New York: Elsevier, 1990, Vol. 4, Ch. 7, pp. 255-292.

Chu, N.C., J.A. Kong, H.A. Yueh, S.V. Nghiem, J.G. Fleischman, S. Ayasli, and R.T. Shin. "Variance of Phase Fluctuations of Waves Propagation through a Random Medium." *J. Electromag. Waves Appl.* Forthcoming.

Chu, N.C., J.A. Kong, H.A. Yueh, S.V. Nghiem, J.G. Fleischman, S. Ayasli, and R.T. Shin. "Variance of Phase Fluctuations of Waves Propagating through a Random Medium." *J. Electromag. Waves Appl.* June 1990.

Habashy, T.M., S.M. Ali, and J.A. Kong. "Input Impedance Parameters and Radiation Pattern of Cylinderical-Rectangular and Wraparound Microstrip Antennas." *IEEE Trans. Antennas Propag.* 38(5): 722-731 (1990).

Habashy, T.M., M. Moldoveanu, and J.A. Kong. "Inversion of Permittivity and Conductivity Profiles Employing Transverse-Magnetic Polarized Monochromatic Data." SPIE 1990 International Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, California, July 8-13, 1990.

Habashy, T.M., S.M. Ali, J.A. Kong, and M.D. Grossi. "Dyadic Green's Functions in a Planar Stratified, Arbitrarily Magnetized Linear Plasma." *Radio Sci.* Forthcoming.

Habashy, T.M., M. Moldoveanu, and J.A. Kong. "Inversion of Permittivity and Conductivity Profiles Employing Transverse-Magnetic Polarized Monochromatic Data." SPIE 1990 International Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, California, July 8-13, 1990.

Han, C.H., J.A. Kong, T.M. Habashy, and M.D. Grossi. "Principles of VLF Antenna Array Design in Magnetized Plasmas." URSI National Radio Science Meeting, Boulder, Colorado, January 3-5, 1990.

Han, C.H., J.A. Kong, T.M. Habashy, and M.D. Grossi. "Principles of VLF Antenna Array Design in Magnetized Plasmas." URSI National Radio Science Meeting, Boulder, Colorado, January 3-5, 1990.

Kiang, J.F., S.M. Ali, and J.A. Kong, "Modelling of Lossy Microstrip Lines with Fine Thickness," In *Progress In Electromagnetics Research.* Ed. J.A. Kong. New York: Elsevier, 1990, Vol. 4, Ch. 3, pp. 85-117.

Kiang, J.F., S.M. Ali, and J.A. Kong. "Integral Equation Solution to the Guidance and Leakage Properties of Coupled Dielectric Strip Waveguides." *IEEE Trans. Microwave Theory Tech.* 38(2): 193-203 (1990).

Kong, J.A., S.H. Yueh, H.H. Lim, R.T. Shin, and J.J. van Zyl. "Classification and Maximum Contrast of Earth Terrain Using Polarimetric Synthetic Aperture Radar Images." In *Progress in Electromagnetics Research.* Ed. J.A. Kong. New York: Elsevier, 1990, Vol. 3, Ch. 6, pp. 327-370.

Lam, C.W., S.M. Ali, and J.A. Kong. "The Propagation Characteristics of Signal Lines with Crossing Strips in Multilayered Anisotropic Media." *J. Electromag. Waves Appl.* 4(10): 1005-1021 (1990).

Lee, C.F., R.T. Shin, J.A. Kong, and B.J. McCartin. "Absorbing Boundary Condions on Circular and Elliptic Boundaries." *J. Electromag. Waves Appl.* 4(10): 945-962 (1990).

[55] H. Lee, S.M. Ali, and J.A. Kong, "Hybrid-Mode Analysis of High-Tc Superconducting Planar Transmission Lines," submitted to Progress In Electromagnetics Research Symposium, Cambridge, Massachusetts, July 1-5, 1991.

Lee, H., S.M. Ali, and J.A. Kong. "Hybrid-Mode Analysis of High-T_c Superconducting Planar Transmission Lines." Submitted to the Progress In Electromagnetics Research Symposium, Cambridge, Massachusetts, July 1-5, 1991.

Lee, C.F., R.T. Shin, and J.A. Kong. "Fine Difference Method for Electromagnetic Scattering Problems," In *Progress In Electromagnetics Research.* Ed. J.A. Kong. New York: Elsevier, 1990, Vol. 4, Ch. 11, pp. 373-442.

Lim, H.H., S.H. Yueh, R.T. Shin, and J.A. Kong. "Correlation Function for a Random Collection of Discrete Scatterers." Tenth International Geoscience and Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990.

Melville, W.K., D.V. Arnold, J.A. Kong, A.T. Jessup, E. Lamarre, R.H. Stewart, and W.C. Keller. "Measurements of EM Bias at Ku and C Bands." OCEANS'90, Washington, D.C., September 24-26, 1990.

Melville, W.K., J.A. Kong, R.H. Stewart, W.C. Keller, D. Arnold, A.T. Jessup, and E. Lamarre. "Measurements of Sea-State Bias at Ku and C Bands." URSI International Commission F meeting, Hyannis, Massachusetts, May 16-18, 1990.

Nghiem, S.V., M. Borgeaud, J.A. Kong, and R.T. Shin. "Polarimetric Remote Sensing of Geophysical Media with Layer Random Medium Model." In *Progress In Electromagnetics Research.* Ed. J.A. Kong. New York: Elsevier, 1990, Vol. 1, Ch. 3, pp. 1-73.

Nghiem, S.V., J.A. Kong, and T. Le Toan. "Electromagnetic Wave Modeling for Remote Sensing." International Conference on Directions in Electromagnetic Wave Modeling, New York, October 22-24, 1990.

Nghiem, S.V., M. Borgeaud, J.A. Kong, and R.T. Shin. "Polarimetric Remote Sensing of Geophysical Media with Layer Random Medium Model." Progress In Electromagnetics Research. Ed. J.A. Kong. New York: Elsevier, 1990, Vol. 3 Ch. 1, pp. 1-73.

Nghiem, S.V., J.A. Kong, R.T. Shin, H.A. Yueh, and R. Onstott. "Theoretical Models and Experimental Measurements for Polarimetric Remote Sensing of Snow and Sea Ice." URSI International Commission F meeting, Hyannis, Massachusetts, May 16-18, 1990.

Nghiem, S.V., J.A. Kong, and R.T. Shin. "Study of Polarimetric Response of Sea Ice with Layered Random Medium Model." Tenth International Geoscience and Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990.

Nghiem, S.V., J.A. Kong, and T. Le Toan. "Application of Layered Random Medium Model to Polarimetric Remote Sensing of Vegetation." URSI International Commission F meeting, Hyannis, Massachusetts, May 16-18, 1990.

Sheen, D.M., S.M. Ali, M.D. Abouzahra, and J.A. Kong. "Application of the Three Dimensional Fine Difference Time-Domain Method to the Analysis of Planar Microstrip Circuits." *IEEE Trans. Microwave Theory Tech.* 38(7): 849-857, (1990).

Tsuk, M.J., and J.A. Kong. "A Hybrid Method for the Calculation of the Resistance and Inductance of Transmission Lines with Arbrary Cross-Sections." Submitted to *IEEE Trans. Microwave Theory Tech.*

Tulintseff, A.N., S.M. Ali, and J.A. Kong, "Input Impedance of a Probe-Fed Stacked Circular Microstrip Antenna." *IEEE Trans. Antennas Propag.* Forthcoming.

Veysoglu, M.E., H.A. Yueh, R.T. Shin and J.A. Kong. "Polarimetric Passive Remote Sensing of Periodic Surfaces." *J. Electromag. Waves Appl.* 5(3): 267-280 (1991).

Yueh, S.H., and J.A. Kong. "Analysis of Diffraction from Chiral Gratings." *J. Electromag. Waves Appl.* Forthcoming.

Yueh, S.H., J.A. Kong, and R.T. Shin. "Calibration of Polarimetric Radars Using In-Scene Reflectors." In *Progress In Electromagnetic Research.* Ed. J.A. Kong. New York: Elsevier, 1990, Vol. 3, Ch. 9, pp. 451-510.

Yueh, S.H., J.A. Kong, and R.T. Shin. "Calibration of Polarimetric Radars Using In-Scene Reflectors." Tenth International Geoscience and Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990.

Yueh, S.H., J.A. Kong, R.T. Shin, and H.A. Zebker. "Statistical Modelling for Polarimetric Remote Sensing of Earth Terrain." Tenth International Geoscience and Remote Sensing Symposium (IGARSS'90), College Park, Maryland, May 20-24, 1990.

Yueh, S.H., J.A. Kong, J.K. Jao, R.T. Shin, H.A. Zebker, T. Le Toan, and H. Öttl. "K-distribution and Polarimetric Terrain Radar Clutter," In *Progress In Electromagnetics Research.* Ed. J.A. Kong. New York: Elsevier, 1990, Vol. 3, Ch. 4, pp. 237-275.

Yueh, H.A., J.A. Kong, R.T. Shin, H.A. Zebker, and T. Le Toan. "K-distribution and Multi-Frequency Polarimetric Terrain Radar Clutter." *J. Electromag. Waves Appl.* Forthcoming.

Yueh, H.A., R.T. Shin, and J.A. Kong, "Scattering from Randomly Oriented Scatterers with Strong Permittivity Fluctuations." *J. Electromag. Waves Appl.* 4(10): 983-1004 (1990).