Section 3 Electromagnetics

Chapter 1 Electromagnetic Wave Theory and Applications.

Chapter 1. Electromagnetic Wave Theory and Applications

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Professor Jin Au Kong and his research group work in the areas of electromagnetic wave theory and applications. They are studing applications to microelectronic integrated circuits, microstrip antennas, geophysical subsurface probing, SAR imaging and microwave remote sensing, and transient electromagnetic pulse propagation and coupling problems. The study of electromagnetic wave propagation in integrated circuits is motivated by the need to achieve condensed circuit packages, shorter rise times, and smaller pulse widths without causing large signal distortion and crosstalk. The methods of characteristics and integral transform based on scattering parameters are used to study the transient response.

Realistic theoretical models that are applicable to the active and passive remote sensing of plowed fields, atmospheric precipitation, vegetation, and snow fields have been developed. The development of these theoretical models has been strongly motivated by the need for accurate data analysis and interpretation, and scene simulation characteristics. Under the consideration that sea ice is a tilted uniaxial medium, the observed strong cross-polarized return in the bistatic scattering coefficients is successfully predicted from the theoretical model. Extensive work has been accomplished in the development of theoretical models and applications to polarimetric remote sensing and terrain classification.

1.1 Electromagnetic Waves in Multilayer Media

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To provide shorter interconnects between chips, modern multilayer integrated circuit packages for high-performance mainframe computers employ not only conventional striplines, but also vertical transmission lines or so-called vias. Because vias may have the same length as the striplines, the study of transient electromagnetic wave propagation on the vias is equally indispensible to the understanding of the speed at which the multilayer integrated circuits can operate.

Idealized circuit packages consisting of circular vias going through circular holes in the ground planes that separate different layers of equal thickness are being considered. When only one via is present, we show that, by treating the layer between two ground planes as a radial waveguide driven by a coaxial feed and making use of symmetry, the equivalent network parameters for each layer can be obtained. The multiple layers constitute a periodic structure and presents little difficulty in computing the total transmission matrix. We also studied an infinite array of vias and holes with equal spacing along two perpendicular directions. By virtue of the image theory, the problem is reduced to a coaxial transmission line with square outer wall and periodic circular diaphragm discontinuities. Both variational approaches as well as the integral equation method can be applied to the calculation of the characteristic impedance, the junction impedance, and the effective propagation constant. The transient response is then obtained by performing the fast Fourier transform on the frequency domain response or by direct Laplace inversion when the dispersion of junction capacitances is negligible. Our numerical results based on the dimensions of an actual package show that the degree of reflection and signal distortion becomes intolerable when the input rise time is shorter than 500 ps.

Another problem of practical interest in microelectronic packaging is the study of propagation characteristics of a shielded microstrip line in the presence of crossing strips. If the microstrip line and the crossing strips are placed at two different interfaces of a three-layer medium bounded by two parallel conducting plates, the crossing strips are assumed to be periodic and the three layers to be uniaxially anisotropic.

We apply the network analytical method of electromagnetic fields to the hybrid-mode analysis of the frequency dependent characteristics of the structure. The transverse fields in each region are expressed by their Fourier transform and a Floquet harmonic representation. Using Maxwell's equations and applying boundary conditions, we obtain a set of coupled integral equations for the current distributions on the microstrip line and the crossing metallic strips.

The determinable equation for the dispersion relation can be derived by applying Galerkin's procedure to the derived set of coupled integral equations. The Brillouin diagrams are obtained numerically by seeking the roots of the obtained eigenvalue equation. The stopband properties are numerically presented as a function of the spacing, length, and width of the crossing metallic strips. The effects of the material and geometrical parameters are also investigated.

The dyadic Green's function approach is used to formulate the integral equations for the signal line and crossing strip currents. Galerkin's procedure is applied to obtain the determinantal equation for the dispersion relation. The effects of substrate material on the propagation characteristics are being investigated numerically. We find that weak anisotropy in the second layer does not affect the position and the width of the stopband much. By the proper choice of substrate material, one can minimize the width of the first stopband. At high frequencies, we encounter higher order stopbands which are due to the interaction with higher order modes of the signal line.

The transient fields of a current source on a layered medium are calculated by using the double deformation technique, in which complex integrals are deformed in the transverse wavenumber and frequency planes. Singularities from these complex planes correspond to physical modes of the structure, such as guided and leaky waves, and the relative importance of each to the overall response can be discovered. Unlike the Cagniard-de Hoop method, double deformation can be applied to dispersive and dissipative media. Also, the causality of the electromagnetic signal can be shown analytically.

A modification to the double deformation technique is developed, which consists of splitting the Fourier transform of the source current into two halves, one for times before the arrival at the observation point, and one after. This modification greatly increases the range of sources to which the double deformation technique can be applied. Another advantage of the modification is the individual causality and continuity of each mode.

Results have been computed both for line and strip currents on the surface of a coated perfect conductor, for cases where the dielectric coating is both lossless and dissipative. In most cases, only a small number of modes suffices to reproduce the important features of the response, including the arrivals of reflected and lateral rays. The importance of each type of arrival depends on certain features of the time function, especially the initial slope. The response due to a strip current resembles that of a line current, with some smoothing of the sharper features.

A rigorous dyadic Green's function formulation for the periodic structure is derived to study the dispersion properties of single and coupled signal lines periodically loaded with crossing strips. The passband and stopband characteristics are investigated when crossing strips are of finite or infinite length.

For crossing strips of finite length, the stopband properties are mainly affected by the period, the length of crossing strips, and the separation between the signal and crossing strips. Also, at higher frequencies, higher order stopbands occur. For crossing strips of infinite length, attenuation along the signal line exists over the whole frequency range due to the power guided by the travelling wave along crossing strips.

The complex resonant frequencies of the open structure of a microstrip antenna consisting of two circular microstrip disks in a stacked configuration are rigorously calculated as a function of the layered parameters and the ratio of the radii of the two disks. By using a dyadic Green's function formulation for horizontally stratified media and the vector Hankel transform, the mixed boundary value problem is reduced to a set of coupled vector integral equations. By employing Galerkin's method in the spectral domain, the complex resonant frequencies are calculated and convergence of the results is demonstrated. It is shown that for each mode, the stacked circular microstrip structure has dual resonant frequencies which are associated with the two coupled constitutive resonators of the structure and a function of the mutual coupling between the two disk resonators. This mutual coupling is a function of the geometrical configuration of the stacked structure, the layered parameters, permittivities, permeabilities, and heights, and the ratio of the radii of the two disks. The dual frequency behavior of the stacked microstrip structure may be used to broaden the bandwidth or to provide for dual frequency use of the antenna.

Solutions to electromagnetic plane wave scattering by a coated perfectly conducting cylinder are being investigated. The scattering of cylindrical structures serves as a model for the study of radio wave diffraction over the earth and radar cross section prediction. To obtain a solution that converges quickly in the high frequency limit, the Watson Transformation is used to convert eigenfunction series solution into a contour integral. This is done by mathematically expressing a series summed at integer values as an integral with its contour path tightly encircling the real axis. The contour integral can be easily evaluated by deforming the integration path to encompass the upper half plane. With the new contour, the integral is calculated by picking up the residues in the upper half plane. The resulting residue series, representing the diffraction field, is quickly convergent at high frequencies. In the shadow region, because no incident or reflected field exists, all radiation in the shadow region can be calculated by the residue series solution. In the context of ray optics, all scattering due to diffraction originates from rays that "creep" around the air-coating interface of the cylinder. Each term of the residue series represents an excited creeping wave mode. The expression for each term of the residue series yields a mode amplitude and a propagation constant for the corresponding mode. The total diffracted field is the sum of the radiation due to all of the creeping wave modes.

We also calculate the radar cross-section of a two-dimensional slot in an infinite ground plane with an incident TM wave. In formulating the integral equation, the problem is separated into two regions. The region below the ground plane is treated as a parallel plate waveguide. In the region above the ground plane, the slot aperture is replaced with a magnetic surface current sheet, and the ground plane is removed by adding the necessary image sources. In utilizing the method of moments, Galerkin's method is used, with the basis function being a pulse function.

This two-dimensional slot can be used to predict the contribution to the total RCS of surface features in vehicles, such as door gaps. This two-dimensional problem best approximates the three-dimensional problem when the slot width is small compared to the wavelength, the slot length is longer than a few wavelengths, and the incident plane wave's magnetic field is parallel to the slot. In this case, the contribution from the ends of the slots is small, and the transverse electric field does not contribute significantly because this component cannot propagate into the slot. In addition to the case where the slot is empty and is short circuited, the slot can be filled with any material and can be backed with some material other than a perfect conductor.

We have incorporated double reflection contribution in the computation of radar scattering from flat plate surfaces. An integral expression is derived by applying the tangent plane approximation at each surface, and correctly accounting for the potentially near-field interactions between the two perfectly conducting plates. The initial complexity of this expression necessitates numerical evaluation of the integrals and results in a large computational burden. The requirement of numerical integration is eliminated, however, by applying the method of Stationary Phase and expanding quadratically the exact interplate phase term. The two surface integrations are replaced by line integrals using Stokes' Theorem, and for polygonal plates, the contour is subdivided into linear segments on which the integration is performed analytically. In the case where the conducting plates are loaded with one or more layers of dielectric, the equivalent electric and magnetic surface currents are derived by using the reflection coefficients at each plate.

The resulting field expressions are derived with sufficient generality to permit incorporation in standard RCS prediction codes allowing arbitrary geometry and illumination. Comparisons with measurements of several simple two-plate targets confirm the accuracy of the predicted field and demonstrate a significant improvement over existing algorithms that neglect multiple reflections or assume a far field interaction between the surfaces.

The pseudo-differential operator approach is being employed to derive absorbing boundary conditions for both circular and elliptic outer boundaries. The pseudo-differential operator approach employed by Engquist and Majda is modified. This modification results in better absorbing boundary conditions. In the case of circular outer boundary, the modified pseudo-differential operator approach leads to a condition equivalent to that of Bayliss and Turkel's second order operator. In the case of elliptic outer boundary, again, this modified pseudo-differential operator approach also yields a second order operator. A close examination of this operator finds that width information of the scatterers enters into the boundary operator. Numerical results demonstrate the effectiveness of these operators.

Finite difference time domain (FDTD) techniques show great promise in their ability to solve three-dimensional problems with arbitrary geometry. One advantage of this method is the ability to model spatially or temporally varying media. Advantages are due to the complete discretization of both space and time. Considering the volume of information being calculated, these techniques are very efficient and are well suited to calculation on future parallel processing computers.

Our work in this area includes development of the algorithms into a general purpose computer code that may be used to solve for the transient response of electromagnetic problems with an arbitrary geometry. In addition to the transient response, frequency domain parameters may be obtained by Fourier transform of the time domain results. Since the fields are calculated throughout space and time all other desired parameters may be calculated from the field quantities.

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

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

The fields at different positions are first calculated. Then the Fourier transform is taken to give the field spectra from which the voltage and current can also be obtained. By using these data, the effective permittivity and the characteristic impedance can be determined.

A finite element time domain technique for two-dimensional time domain scattering of electromagnetic waves is studied. The control region approximation, which calls for Delaunay and Dirichlet tessellation, has been successfully applied to the frequency domain problems in the past. Two double integral terms are obtained by integrating the Helmholtz equation about the Delaunay tessellation. The term involving the Laplace operator can be converted to a closed loop integral of normal derivatives, which can easily be approximated in finite difference manner by utilizing the orthogonal property of Delaunay and Dirichlet tessellation. The remaining term can be approximated by multiplying the field at the node with the area. In the time domain problem, the same approximation is applied to the wave equation, except the term involving time derivatives is used in time marching scheme. Alternatively, as in Yee's algorithm, the first order Maxwell's equations are solved by spatially and temporally separating the electric and magnetic fields. In the case of electric polarization, the electric fields are placed at the nodes and the magnetic fields are placed at the centers of triangular edges. The curl H equation is integrated by applying Stoke's theorem to convert it to a closed loop integral of tangential magnetic fields. This equation can be used to advance electric fields in time. To update the magnetic fields, the second curl equation is used. This equation is approximated in the finite difference manner by utilizing the orthogonality property of the tessellation. The orthogonal property of the tessellation and finite difference approximations are utilized which does not require integration. The equations for the magnetic polarization case can be derived following a similar procedure.

To limit the computation domain, the scatterers are enclosed with artificial outer boundaries. Continuous smooth outer boundaries, such as circles and ellipses, are chosen. The second-order time domain absorbing boundary conditions derived from the pseudo-differential operator approach is imposed at the outer boundaries. These boundary conditions are implemented with the control region approximation to determine necessary field quantities at the boundary. The time domain control region approach has been successfully applied to simple geometries, such as conducting and coated cylinders.

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1.2 Remote Sensing of Earth Terrain

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We have developed the layered random medium model for both active and passive remote sensing of earth terrain. For active remote sensing, the model is applied to convention and polarimetric radar scattering coefficients. For passive remote sensing, the model is used to calculate emissivities and brightness temperatures. Effects of rough surfaces are studied with the Extended Boundary Condition and Small Perturbation Method. EM bias due to rough ocean surface is studied with a two-scale model and the physical optics approximation. Furthermore, intervening effects such as phase fluctuations due to forest foliage, Faraday polarization fluctuations, and wave nonlinear interaction in the ionosphere are investigated.

We derived a mathematically rigorous and fully polarimetric radar clutter model used to evaluate the radar backscatter from various types of terrain clutter such as forested areas, vegetation canopies, snow covered terrains, or ice fields. With this model, we can calculate the radar backscattering coefficients (σ^o) for the multi-channel polarimetric radar returns, in addition to the complex cross correlation coefficients between elements of the polarimetric measurement vector. The complete polarization covariance matrix can be computed and the scattering properties of the clutter environment characterized over a broad range of incident angles and frequencies.

The random medium model with three-layer configuration is developed to study fully polarimetric scattering of electromagnetic waves from geophysical media. This model can account for the effects on wave scattering due to weather, diurnal and seasonal variations, and atmospheric conditions such as ice under snow, meadow under fog, and forest under mist. The top scattering layer is modeled as an isotropic random medium which is characterized by a scalar permittivity. The middle scattering layer is modeled as an anisotropic random medium with a symmetric permittivity tensor with an optic axis that can be tilted due to the preferred alignment of the embedded scatterers. The bottom layer is considered as a homogeneous half-space. Volume scattering effects of both random media are described by three-dimensional correlation functions with variances and correlation lengths corresponding to the strengths of the permittivity fluctuations and the physical sizes of the inhomogeneities, respectively. The strong fluctuation theory is used to derive the mean fields in the random media under the bilocal approximation with singularities of the dyadic Green's functions properly taken into account and effective permittivities of the random media are calculated with two-phase mixing formulas. The distorted Born approximation is then applied to obtain the covariance matrix that describes the fully polarimetric scattering properties of the remotely sensed media.

The three-layer configuration is first reduced to two-layers to observe fully polarimetric scattering directly from geophysical media such as snow, ice, and vegetation. Such media exhibit reciprocity as experimentally manifested in the close proximity of the measured backscattering radar cross-sections σ_{vh} and σ_{hv} and theoretically established in the random medium model with symmetric permittivity tensors. The theory is used to investigate the signatures of isotropic and anisotropic random media on the complex correlation coefficient ρ between σ_{hh} and σ_{vv} as a function of incident angle. For the isotropic random medium, ρ has the value of approximately 1.0. For the untilted anisotropic random medium, ρ has complex values with both the real and imaginary parts decreased as the incident angle is increased. The correlation coefficient ρ is shown to contain information about the tilt of the optic axis in the anisotropic random medium. As the tilted angle becomes larger, the magnitude of ρ is maximized at a larger incident angle where the phase of ρ changes its sign.

The effects on polarimetric wave scattering due to the top layer are identified by comparing the three-layer results with those obtained from the two-layer configuration. The theory is used to investigate the effects on polarimetric radar returns due to a low-loss and a lossy dry-snow layers covering a sheet of thick first-year sea ice. For the low-loss snow cover, both σ_{hh} and σ_{vv} are enhanced compared to those observed from bare sea ice. Furthermore, the boundary effect is manifested in the form of the oscillation on σ_{hh} and σ_{vv}. The oscillation can also be seen on the real and imaginary parts of the correlation coefficient ρ. The magnitude of ρ, however, does not exhibit the oscillation while clearly retaining the same characteristics as observed directly from the uncovered sea ice. In contrast to the low-loss case, the lossy top layer can diminish both σ_{hh} and σ_{vv} and depress the boundary-effect oscillation. When the thickness of the lossy top layer increases, the behavior of the correlation coefficient ρ becomes more and more similar to the isotropic case signifying that the information from the lower anisotropic layer is masked. At appropriate frequency, the fully polarimetric volume scattering effects can reveal the information attributed to the lower layer even if it is covered under another scattering layer. Due to the physical base, the random medium model renders the polarimetric scattering information useful in the identification, classification, and radar image simulation of geophysical media.

We have derived the dyadic Green's function for a two-layer anisotropic medium. The Born approximation is used to calculate the scattered fields. With a specified correlation function for the randomness of the dielectric constant, the backscattering cross-sections are evaluated. The analytic expressions for backscattering coefficients are shown to include depolarization effects in the single-scattering approximation. It is also shown that the backscattering cross-section (per unit area) of horizontal polarization can be greater than that of vertical polarization even in the case of half-space. The bistatic scattering coefficients are first calculated and then integrated over the upper hemisphere to be subtracted from unity to obtain the emissivity. The principle of reciprocity is then invoked to calculate the brightness temperatures. It is shown that both the absorptive and randomly fluctuating properties of the anisotropic medium affect the behavior of the resulting brightness temperatures both in theory and in actual controlled field measurements. The active and passive results are favorably matched with the experimental data obtained from the first-year and the multiyear sea ice.

Electromagnetic wave propagation and scattering in an anisotropic random medium is being examined with Dyson equation for the mean field which is solved by bilocal and nonlinear approximations and with Bethe-Salpeter equation for the correlation of field was derived and solved by ladder approximation. The effective propagation constants are calculated for the four characteristic waves associated with the coherent vector fields propagating in an anisotropic random medium layer, which are the ordinary and extraordinary waves with upward and downward propagating vectors. The longitudinal-component of the effective propagation constant of the upward propagating wave is different from the negative of that of the downward propagating wave, not only for the extraordinary wave but also for the ordinary wave. This is due to the tilting of the optic axis which destroys the azimuthal symmetry.

To describe the effect of the random medium on electromagnetic waves, the strong permittivity fluctuation theory, which accounts for the losses due to both of the absorption and the scattering, is used to compute the effective permittivity of the medium. For a mixture of two components, only the frequency, the correlation lengths, the fractional volume, and the permittivities of the two constituents are needed to obtain the polarimetric backscattering coefficients. Theoretical predictions are illustrated by comparing the results with experimental data for vegetation fields and sea ice.

The correlation function plays an important role in relating the electrical response of geophysical media to its physical properties. Volume scattering effects of electromagnetic waves from geophysical media such as vegetation canopies and snow-ice fields have been studied by using the random medium models. The correlation functions used in the random medium model have been extracted from digitized photographs of cross-sectional samples for snow and lake ice and artificially grown saline ice. It was shown that the extracted correlation lengths corresponded to the physical sizes of ice grains, air bubbles, and brine inclusions. Also the functional forms of the extracted correlation functions were shown to be dependent on the shape and orientation of embedded inhomogeneities.

Extending Debye's analytical work, we have derived the correlation function and the correlation length for isotropic random medium with spherical inclusions. The correlation function study is also generalized to randomly distributed prolate spheroids with preferred alignment in the vertical direction for the anisotropic random medium. A scaling scheme is employed to transform the surface equation of prolate spheroids to that of spheres so that the same approach in the isotropic case can be utilized to derive the correlation function. Most of geophysical media are complex materials such as wet snow which is a mixture of air, ice grains, and water content and multi-year sea ice, which consists of pure ice, air bubbles, and brine inclusions. Therefore, the correlation function study for three-phase mixtures is also established. Two different kinds of inclusions with spherical and spheroidal shapes are considered. It is found that there is a close relationship between the form of the correlation function and the distribution, geometrical shape, and orientation of the scatterers. Also, the calculated correlation lengths are related to the fractional volumes and total common surface areas. These results can be utilized to identify the feature signature and characteristics through its microscopic structure. For instance, dry or slush snow can be distinguished from grain sizes, water contents, and density via the comparison of the variances and correlation lengths. The form of the correlation function provides the information about the physical shape and alignment of brine inclusions in addition to the concentration of brine inclusions versus air bubbles for tracing sea-ice signatures such as thick first-year sea ice and multi year sea ice.

The scattering of electromagnetic waves from a randomly perturbed periodic terrain surface is formulated by the Extended Boundary Condition (EBC) method and solved by the small perturbation method (SPM). The scattering from periodic surface is solved exactly and this solution is used in the SPM to solve for the surface currents and scattered fields up to the second order. The random perturbation is modeled as a Gaussian random process. The theoretical results are illustrated by calculating the bistatic and backscattering coefficients. It is shown that as the correlation length of the random roughness increases, the bistatic scattering pattern of the scattered fields show several beams associated with each Bragg diffraction direction of the periodic surface. When the correlation length becomes smaller, then the shape of the beams become broader. Kirchhoff approximation results show a good agreement with EBC/SPM method results for the hh and vv polarized backscattering coefficients for small angles of incidence. However, the results obtained from the

EBC/SPM method give significant depolarized returns when the incident direction is not perpendicular to the row direction of the periodic surface which the Kirchhoff approximation is unable to predict.

The EM bias in altimetry can be solved more accurately by modeling the ocean surface with a two-scale model and by using a physical optics technique. For normal incidence, a Gaussian height probability density, and for small slopes of the large-scale ocean waves, the physical optics integral can be solved for the backscattered power by using the saddle point method. The ocean can be divided into large- and small-scales by choosing a separation wavenumber. The small-scale height variance can be measured from experimental data and the small-scale slope and curvature variances can be estimated by using a suitable wavenumber spectrum. Then, considering the wind speed and small-scale height variance, the EM Bias can be estimated by calculating the centroid of the backscattered power. The EM bias has been calculated by using this method and compared with experimental data of wind speed and wave height statistics.

We have calculated the phase degradation that an electromagnetic wave undergoes when it propagates through a forest, scatters off a target, and then propagates back through the forest to the radar (two-way problem). The problem is configured with a transmitter located above the forest and a receiver located within it. The forest is modeled as a two-layer random medium (two boundaries separating three regions), with the first layer representing free space, the second layer representing the forest, and the third layer representing the ground. Scattering is considered to be mainly from the leaves, a good approximation for frequencies of 1 GHz and higher. Hence, the forest is modeled as a layer of identical scatterers (representing the leaves) randomly distributed in an air background. The scatterers are characterized with correlation functions, which are statistical descriptions of the physical size of the scatterers. The effective permittivity of the medium is calculated by using strong fluctuation theory, that accounts for the fact that the permittivity of leaves that of air may be quite different (permittivity fluctuation variance not much less than one). Defining the permittivity of the medium as the sum of the effective permittivity and an assumed fluctuating permittivity accounts for the scattering properties of the medium.

Phase fluctuations are calculated for the case of a plane wave normally incident upon the forest. The wave undergoes scattering as it propagates through the medium. The total electric field in the medium is thus approximated by an unperturbed incident field and a first-order scattered field. Maxwell's equations are used with this total field to obtain the wave equation. The fluctuating part of the resulting expression, which comes from the assumed fluctuating permittivity, is isolated and treated as a source term. The normalized first-order scattered field, containing information about the phase fluctuations, is then calculated by using a Green's function for an unbounded medium (thereby neglecting boundary effects). The variance of the scattered field is computed, giving information about the magnitude of the phase fluctuations.

The physical characteristics of correlation length and scatterer permittivity must be known to properly model the medium. These characteristics are determined by matching experimental data on attenuation through forests with results from a code that calculates attenuation by using the strong permittivity fluctuation theory. The numerical results of the phase fluctuation calculations were compared to those of a model using the paraxial approximation. Both models converge to the same result in the paraxial limit.

As radio waves propagate through the ionosphere, wave scattering can occur as a result of ionospheric density irregularities which give rise to fluctuations in Faraday rotation angles, known as Faraday Polarization Fluctuations (FPF). FPF have been observed with low-orbit satellite beacon signals transmitted at frequencies 20, 40, and 54 MHz, and also with geostationary satellite signals at 136 MHz. It has been shown experimentally that when the linearly polarized waves, decomposed into two characteristic wave modes, were measured separately after transionospheric propagation, there was a loss of correlation between the two characteristic wave modes. Diffractive scattering of radio waves by ionospheric density irregularities is responsible for this phenomenon. The density irregularities were considered to be isotropic and modeled by correlation functions having the same correlation length in all directions. Ionospheric plasma, however, is magnetized by the geomagnetic field and ionospheric density irregularities tend to elongate along the magnetic field. The elongation results in the formation of field-aligned rod-like irregularities. Sheet-like irregularities were also predicted theoretically and measured recently. Therefore, the geomagnetized ionosphere with density irregularities is modeled as a gyrotropic random medium and the effects of both rod-like and sheet-like random density irregularities in causing FPF of VHF radio signals are studied by means of three-dimensional correlation functions.

The model is used to explain the intense FPF observed in polarimetric records of 136-MHz satellite signals received at Ascension Island in 1980 and 1981. The VHF signals were transmitted from the geostationary satellite SIRIO and propagated through the ionosphere near the Appleton equatorial anomaly crest where the ambient plasma density was high especially during the 1980 solar-maximum period. For rod-like irregularities, the theoretical results predict the field-aligned enhancement of FPF. The enhancement is shown to be stronger for longer rod-like irregularities. Furthermore, the results also demonstrate an inverse relation between the strength of FPF and the wave frequency. For sheet-like irregularities, the results also exhibit the field-aligned enhancement of FPF and the decreasing FPF strength with increasing propagation angle. The difference, however, is that the FPF strength due to the sheet-like irregularities have slower decreasing rates at small propagation angle and have larger values at large propagation angle than the FPF due to the rod-like irregularities. For VHF waves, the RMS FPF due to the rod-like and the sheet-like irregularities are quite distinctive. This suggests that the RMS FPF data with multi-frequencies and multi-propagation angles can be used to infer the size and shape of ionospheric irregularities.

During the transionospheric propagation of a high power radio wave beam, the nonuniform electromagnetic field interacts with the background plasma and gives rise to a ponderomotive force and a thermal pressure force. Both of the two nonlinear forces mainly act on the electrons, but eventually will have an effect on the ions through the ambipolar diffusion process. The spatial redistribution of the plasma density caused by the actions of these forces will change the local plasma permittivity along the beam path and consequently lead to the focusing of the radio wave beam.

We examine the self-focusing phenomena by taking into account both the ponderomotive force and the thermal pressure force as the two primary mechanisms. The threshold power intensity is determined by balancing the natural diffraction and the nonlinear focusing effects of the wave beam. The focal length for the concerned process is then estimated by solving the nonlinear wave equation.

To illustrate the self-focusing process, we carried out a series of numerical simulation for high frequency beams with various initial beam widths propagating in the ionospheric plasmas. The peak field intensity and the electron temperature along the beam path are calculated numerically. It is also shown that, the thermal pressure force is predominant over the ponderomotive force in large incident beam width cases; however, the ponderomotive force is more significant if the beam width is small.

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1.3 Remote Sensing of Sea Ice

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For active and passive microwave remote sensing, the correlation function used in the random medium model provides a direct link between electrical behaviors and physical properties of geophysical media. The distribution, shape, size, and orientation of embedded inhomogeneities, such as ice grains in snow and brine inclusions in sea ice, can be characterized by the functional form of the correlation function, the variance, and the correlation lengths. Based on the probability theory, analytical expressions of correlation functions for two-phase mixtures with randomly distributed inclusions of spherical and spheroidal shapes are derived. It is shown that the functional form of the correlation function is determined by the shape and orientation of inclusions while correlation lengths are related to the fractional volume of the scatterers and the total common surface area.

In active and passive microwave remote sensing of sea ice, a correlation function of exponential form is extracted from the photograph of a horizontal thin section taken from a sample of artificially grown saline ice that closely resembles Arctic congelation sea ice. It is found that the extracted correlation lengths are consistent with the published average size of brine pockets. With the application of strong fluctuation theory and the bilocal approximation, the effective permittivity tensor is derived in the low frequency limit for an unbounded uniaxial random medium with two-phase mixtures. By using the extracted correlation lengths, the effective permittivity tensor is computed as a function of fractional volume of brine inclusions and compared with in situ measurements at 4.8 and 9.5 GHz.

We have also derived a general mixing formula for discrete scatterers immersed in a host medium. The inclusion particles are assumed to be ellipsoidal. The electric field inside the scatterers is determined by quasi-static analysis and assuming the diameter of the inclusion particles to be much smaller than the wavelength. The results are applicable to general multiphase mixtures, and the scattering ellipsoids of the different phases can have different sizes and arbitrary ellipticity distribution and axis orientation, i.e., the mixture may be isotropic or anisotropic. The resulting mixing formula is nonlinear and implicit for the effective complex dielectric constant because the approach in calculating the internal field of scatterers is self-consistent. Still, the form is especially suitable for iterative solution. The formula contains a quantity called the apparent permittivity. With different variations of this quantity, the result leads to the generalized Lorentz - Lorenz formula, the generalized Polder - van Santen formula, and the generalized coherent potential - quasi-crystalline approximation formula. The results have been applied to calculating the complex effective permittivity of snow and sea ice.

For active remote sensing, the volume scattering effects of snow-covered sea ice are studied with a three-layer random medium model for microwave remote sensing. The strong fluctuation theory and the bilocal approximation are applied to calculate the effective permittivities for snow and sea ice. The wave scattering theory in conjunction with the distorted Born approximation is then used to compute bistatic coefficients and backscattering cross-sections. Theoretical results are illustrated by matching experimental data for dry snow-covered thick first-year sea ice at Point Barrow. The radar backscattering cross-sections are seen to increase with snow cover for snow-covered sea ice, due to the increased scattering effects in the snow layer. The results derived can also be applied to passive remote sensing by calculating emissivity from the bistatic scattering coefficients.

For passive remote sensing, snow-covered ice field are studied with a three-layer model, an isotropic random medium layer overlying an anisotropic random medium. We have calculated the dyadic Green's functions of the three-layer medium and the scattered electromagnetic intensities with Born approximation. The backscattering cross-sections are evaluated for active microwave remote sensing. The theoretical approach can be extended to derive the bistatic scattering coefficients. After integrating the bistatic scattering coefficients over the upper hemisphere and subtracting from unity, we can also compute the radiometric brightness temperatures for passive microwave remote sensing by invoking the principle of reciprocity.

Since both snow and ice exhibit volume scattering effects, we model the snow-covered ice fields with a three-layer random medium model having an isotropic layer to simulate snow, an anisotropic layer to simulate ice, and a bottom one simulating ground or water. The snow and ice are characterized by different dielectric constants and correlation functions. The theoretical results are illustrated for thick first-year sea ice covered by dry snow at Point Barrow and for artificial thin first-year sea ice covered by wet snow at CRREL. The radar backscattering cross-sections are seen to increase with snow cover for snow-covered sea ice because snow gives more scattering than ice. The results are also used to interpret experimental data obtained from field measurements.

We have used strong fluctuation theory to derive the backscattering cross-sections. The study of the strong fluctuation theory for a bounded layer of random discrete scatterers is further extended to include higher order co-polarized and cross-polarized second moments. The backscattering cross-sections per unit area are calculated by including the mutual coherence of the fields due to the coincidental ray paths and that due to the opposite ray paths which are corresponding to the ladder and cross terms in the Feynman diagrammatic representation. It is proved that the contributions from ladder and cross terms for co-polarized backscattering cross-sections are the same, while the contributions for the cross-polarized ones are of the same order. The bistatic scattering coefficients in the second-order approximation for both the ladder and cross terms are also obtained. The enhancement in the backscattering direction can be attributed to the contributions from the cross terms.

A two-layer anisotropic random medium model has been developed for active and passive microwave remote sensing of ice fields. First, dyadic Green's function for this two-layer anisotropic medium is derived. Then, with a specified correlation function for the randomness of the dielectric constant, the backscattering cross-sections are calculated with the Born approximation. It is shown that the depolarization effects exist in the single-scattering process. By treating sea ice as a tilted uniaxial medium, the observed strong cross-polarized return in the bistatic scattering coefficients is successfully predicted from the theoretical model. It is also shown that the backscattering cross-section of horizontal polarization can be greater than that of vertical polarization even in the half-space case. The principle of reciprocity and the principle of energy conservation are invoked to calculate the brightness temperatures. The bistatic scattering coefficients are first calculated and then integrated over the upper hemisphere to be subtracted from unity, in order to obtain the emissivity for the random medium layer. It is shown that both the absorptive and randomly fluctuating properties of the anisotropic medium affect the behavior of the resulting brightness temperatures both in theory and in actual controlled field measurements. The results from active and passive microwave remote sensing match well with the experimental data obtained from the first-year and the multiyear sea ice with detailed ground-truth information.

We have derived the dyadic Green's function for a two-layer anisotropic medium. The Born approximation is used to calculate the scattered fields. With a specified correlation function for the randomness of the dielectric constant, the backscattering cross-sections are evaluated. The analytic expressions for backscattering coefficients are shown to include depolarization effects in the single-scattering approximation. It is also shown that the backscattering cross-section (per unit area) of horizontal polarization can be greater than that of vertical polarization even in the case of half-space. Furthermore, both the absorptive and randomly fluctuating properties of the anisotropic medium affect the behavior of the resulting brightness temperatures both in theory and in actual controlled field measurements. The active and passive results matched favorably with the experimental data obtained from the first-year and the multiyear sea ice.

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1.4 SAR Image Interpretation and Simulation

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For SAR image interpretation, we use the layered random medium model. Earth terrain media, such as vegetation, forest, snow, and ice exhibit strong volume scattering effects. To study polarimetric radar backscatter of earth terrains from the point of view of electromagnetic wave theory, we use a layered random medium model to characterize the terrain clutter. The random medium is described by a background permittivity with a fluctuating component; the randomness of the fluctuation is characterized by a three-dimensional correlation function with a variance and horizontal and vertical correlation lengths. The variance corresponds to the strength of the fluctuation, while the correlation lengths coincide with the geometrical size of the basic scattering elements. The polarimetric backscattering coefficients can be obtained from the electromagnetic wave theory by calculating the covariance matrix of the polarimetric measurement vector.

We developed a wave approach by applying the Born approximation. An integral equation is formulated for the electric field by using the unperturbed Green's function for a layered random medium in the absence of permittivity fluctuations. The random fluctuations are treated as induced scattering sources in the integral equation, which will then be solved by iteration to obtain a Neumann series. The Born approximation is carried out to the second order to include the depolarization effects. Physically, the Born first-order and second-order approximations account, respectively, for a single and double scattering process. The calculated covariance matrix for a layered isotropic random medium has four of its elements equal to zero, indicating absence of correlation between the HV and HH terms and HV and VV terms. The theoretical results are shown to be consistent with measurement data obtained from MIT Lincoln Laboratory.

We have studied the Mueller matrix and polarization covariance matrix for polarimetric radar systems. The clutter is modelled by a layer of random permittivity, described by a three-dimensional correlation function, with variance, and horizontal and vertical correlation lengths. This model is applied by using wave theory with Born approximations carried to the second order, to find the backscattering elements of the polarimetric matrices. It is found that eight out of sixteen elements of the Mueller matrix are identically zero, corresponding to a covariance matrix with four zero elements. Theoretical predictions are matched with experimental data for fields of vegetation.

Among many non-Gaussian statistics, the K-distribution has proven to be useful in characterizing the amplitude distribution of electromagnetic echoes from various objects, including diverse ground surfaces, sea surface, and wave propagation through atmospheric turbulence. We have developed a multivariate K-distribution model for the statistics of fully polarimetric data from earth terrain with polarizations HH, HV, VH, and VV. In this approach, correlated polarizations of radar signals, as characterized by a covariance matrix, are treated as the sum of N n-dimensional random vectors which obey the negative binomial distribution law. Subsequently, an n-dimensional K-distribution, with either zero or non-zero mean, is derived in the limit of infinite illuminated area. The probability density function (PDF) of the K-distributed vector normalized by its Euclidean norm is independent of the parameter α and is the same as that derived from a zero-mean Gaussian-distributed random vector. High-order normalized intensity moments and cumulative density functions (CDF) of experimental data obtained from MIT Lincoln Laboratory and the Jet Propulsion Laboratory are compared with theoretical values of the K-distribution. The above model is well supported by experimental data in the form of polarimetric measurements.

The evaluation of clutter backscatter coefficients for HH, HV and VV polarimetric returns is useful in the design and analysis of optimal radar target detection, discrimination and classification schemes. Another important application is the generation of random clutter returns for Monte-Carlo simulations. A systematic approach for the identification of terrain media such as vegetative canopy, forest, and snow-covered fields is developed using the optimum polarimetric classifier. The covariance matrices for the various terrain cover are computed from theoretical models of random medium by evaluating the full polarimetric scattering matrix elements. The optimal classification scheme makes use of a quadratic distance measure and is applied to classify a vegetative canopy consisting of both trees and grass. Experimentally measured data are used to validate the classification scheme. Theoretical probability of classification error using the full polarimetric matrix are compared with classification based on single features including the phase difference between the VV and HH polarization returns. It is shown that the full polarimetric results are optimal and provide better classification performance than single feature measurements.

Supervised and unsupervised classification procedures are developed and applied to synthetic aperture radar (SAR) polarimetric images to identify its various earth terrain components. For the supervised classification processing, the Bayes technique is utilized to classify fully polarimetric and normalized polarimetric SAR data. Simpler polarimetric discriminates such as the unnormalized and normalized magnitude response of the individual receiver channel returns in addition to the phase difference between the receiver channels are also considered. Covariance matrices are computed for each terrain class from selected portions within the image where ground truth is available under the assumption that the polarimetric data has a multivariate Gaussian distribution. These matrices are used to train the optimal classifier, which in turn is used to classify the entire image. In this case, classification is based on determining the *distances* between the training classes and the observed feature vector, then assigning the feature vector to belong to that training class for which the distance was minimum. Another processing algorithm based on comparing general properties of the Stokes parameters of the scattered wave to that of simple scattering models is also discussed. This algorithm, which is an unsupervised technique, classifies terrain elements based on the relationship between the orientation angle and handedness, or ellipticity of the transmitted and received polarization state. These classification procedures have been applied to San Francisco Bay and Traverse City SAR images. It is shown that fully polarimetric classification yields the best overall performance. Also, in some selected areas where the observed amplitudes of the returns are quite different from those of the training data, classification techniques which were not based on the absolute amplitudes of the returns, e.g., the normalized polarimetric classifier, produced a more consistent result in relation to the ground truth data.

Polarimetric radar backscatter data have been used extensively to classify terrain cover. Since it is difficult to calibrate out the effects of amplitude and phase errors induced by atmospheric effects, path loss, etc., absolute amplitude and phase of radar returns are not reliable features for terrain classification purposes. The use of normalized polarimetric data is proposed so that only the relative magnitudes and phases will be utilized to discriminate different terrain elements. It is shown that the Bayes classification error does not depend on the form of the normalization function if the unknown radar system calibration factor is modeled as a multiplicative term in the received signal. This holds true for arbitrary probabilistic distributed polarizations. Assuming a multivariate Gaussian distribution for the un-normalized polarimetric data, the probability density function (PDF) of the normalized data and its corresponding Bayes classifier distance measure are derived. Furthermore, by assuming a specific form of the covariance matrix for the polarimetric data, exact PDFs are given for HH, HV, VV and span type normalization schemes. Corresponding classification errors are evaluated to verify their independence from all normalization functions.

There is considerable interest in determining the optimal polarizations that maximize the contrast between two scattering classes in polarimetric radar images. We have developed a systematic approach for obtaining the optimal polarimetric matched filter, i.e., the filter that produces maximum contrast between two scattering classes. The maximization procedure involves solving an eigenvalue problem in which the eigenvector corresponding to the maximum contrast ratio is optimal polarimetric matched filter. To exhibit its physical significance, this filter is transformed into its associated transmitting and receiving polarization states written in terms of horizontal and vertical vector components. For the special case where the transmitting polarization is fixed, the receiving polarization which maximizes the contrast ratio is also obtained. Polarimetric filtering is then applied to synthetic aperture radar images. It is shown, both numerically and through the use of radar imagery, that maximum image contrast can be realized when data is processed with the optimal polarimetric matched filter.

We have developed a data processing algorithm that produces maximum contrast between two scattering classes, each represented by its respective covariance matrix. We will derive an optimal linear decision vector or decision functional that maximizes the contrast or expected power return ratio between the two scattering classes. The suboptimal case of a fixed transmit polarization will also be considered. The maximization procedure involves solving an eigenvalue problem in which the the eigenvector yielding this maxima will correspond to the decision functional we seek. To demonstrate the physical significance of the linear weighting decision vector, we transform the vector into its associated transmit and receive polarization state in terms of horizontal and vertical vector components. This technique is then applied to radar imagery to enhance contrast between different classes within a given database.

A clutter model is used to simulate fully polarimetric returns for a coherent, stepped-frequency radar. The objective is to create site-dependent synthetic clutter signatures that can be utilized in a hardware-in-the-loop test system. The fully polarimetric, multi-frequency, and multi-incident angle two-layer anisotropic random medium model is employed to compute the normalized backscatter coefficients of terrain clutter. Polarization covariance matrices are calculated for each of N high resolution range bins, at each of the M discrete frequencies that comprise the stepped-frequency bandwidth. The covariance matrices are decomposed, multiplied by complex Gaussian noise, and weighted according to the random product model to account for the spatial variability of clutter. This generates the normalized electric field backscattered from each of the N range bins, at each of the M discrete frequencies. These fields are coherently added, taking into account the effects of terrain shadowing and overlay, to realize the single-frequency polarimetric return that a radar would measure from the specified terrain. The radar return for each of the other discrete frequencies is computed in a similar manner. In addition, the real-time implementation of this algorithm is considered in the context of synthetic wideband processing. The result of this procedure yields the clutter's coherent phase-history profile. The clutter phase-history returns can then be coherently superimposed on the target phase-history returns. The combined (or clutter only) returns can be reduced to obtain either 1) the coherent high resolution range profile (HRRP) or 2) the non-coherent autocorrelation range profile.

By using the random medium model, synthetic aperture radar (SAR) simulations can now be generated based on ground truth data from a given terrain site. We first match the various elements within the data to the physical parameters previously discussed, which are compiled in a database generated from correlation function studies. Based on these physical terrain parameters, we next use the random medium model to predict the radar backscatter from the various terrain elements in order to generate a range cross-range terrain profile. We have taken into account the change of incident angle along the ground swath as well as the terrain local incident angle, when the terrain backscatter is computed. Finally the effects of fading (i.e., speckle) are incorporated into the simulated imagery. Utilizing this procedure, we are able to simulate the radar measurements which would have been actually recorded had this terrain been imaged by an airborne SAR. There simulations are fully polarimetric. The advantage to terrain simulation using the random medium model is that, in general, most airborne radars operate at either a single frequency, of over some relatively small bandwidth. However, the random medium model allows us to generate simulations of the same terrain for a variety of operating frequencies. In light of this fact, we see that terrain simulation based on the random medium model is an extremely useful tool.

Development of high resolution and autocorrelation range profile algorithms, which are a special case of the above mentioned terrain simulation, is continuing. The primary modification altered the way in which the terrain was sectioned into high resolution range bins. Formerly these bins were evenly spaced on a flat terrain; however, spacing was not uniform when terrain elevation information was added. The new methodology takes this effect into account. Now the terrain scattering elements, located in each range bin are evenly separated both in the case of a flat terrain and for regions in which ground elevation occurs. Since most terrain regions are not uniformly flat, this new algorithm for partitioning the terrain represents an improvement over the previous model.

Polarimetric calibration algorithms are developed to provide exact solutions for completely general target choices in polarimetric radar calibration. The transmitting and receiving ports of the polarimetric radar are modeled by two unknown polarization transfer matrices. These two matrices are found by using three in-scene reflectors with different scattering matrices. We have analyzed all possible combinations of calibration targets and obtained solutions to all cases. Thus, if three scatterers with known scattering matrices, not necessarily man-made, are known to exist within a radar image, the whole image can be calibrated by using the obtained exact solutions.

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1.5 Microwave and Millimeter Wave Integrated Circuits

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

An integral equation formulation based on dyadic Green's function is derived to solve for the dispersion relation of single and coupled dielectric strip waveguides. We are able to predict the leakage properties of them from these dispersion relations. For single dielectric strip waveguide, it is observed that the leakage occurs when the effective refractive index is smaller than that of a surface wave mode in the background medium. It is also observed that if the lowest TE-like mode is leaky, the lowest TM-like mode is non-leaky. The reverse is also true when the lowest order mode leaks, the surface wave mode of opposite polarization is excited. When the higher order mode leaks, the surface wave modes of both polarizations can be excited.

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

Conventional microstrip antennas consisting of a single perfectly conducting patch on a grounded dielectric slab, have received much attention in recent years due to their many advantages including low profile and light weight. To increase the bandwidth, a number of microstrip patches can be stacked in multilayer configurations, introducing additional resonances in the frequency range of interest and achieving wider bandwidths. We have developed a method of analyzing coaxial probe-fed microstrip antenna consisting of two circular microstrip disks in a stacked configuration.

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

By using the dyadic Green's function formulation, a rigorous analysis of the two stacked circular microstrip disks in a layered medium is performed. A set of coupled integral equations for the current distribution on the disks is derived by using the vector Hankel transform. This coupled set is then solved using Galerkin's method. The choice of the current basis functions is based on the currents of the magnetic wall cavity. Complex resonant frequencies are calculated as a function of the layered substrate, permittivities and thicknesses, and the ratio of the two disks radii. The resonant frequencies of two different stacked configurations are studied as function of the coupling interaction. Critical coupling between the two resonators occurs at the point where the real part of the resonance curves for the two isolated resonators intersect. The splitting of the complex resonance curves at this point is a function of the strength of the coupling between the two resonators. The dual frequency or wide band operation is shown to be achieved by changing the coupling coefficient. The input impedance and radiation patterns of the stacked microstrip antenna is calculated as a function of the layered substrate, permittivities and thicknesses, and the ratio of the radii of the two disks.

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

We also formulated the problem in terms of a Weber transform that allows the development of Green's function of the layered medium with the probe and the microstrip patch as part of the medium. Using the Weber transform automatically enforces the boundary conditions on the probe and patch. This allows one to cast the problem as the solution of a set of two coupled integral equations governing the tangential component of the electric field across the aperture of the coaxial line feed and the interface where the patch lies. This set is then solved by using the method of moments. The current distribution on both the probe and the patch is then computed from the component of the magnetic field tangential to their surfaces. Furthermore, from the computed electric field across the aperture of the coaxial line feed, one obtains the reflection coefficient for the TEM mode which allows computation of the input impedance across the terminals of the probe.

Cylindrical microstrip antennas find many applications in high speed aircrafts and space vehicles because of their conformity with the aerodynamical structure of these vehicles. We address the realistic problem of radiation from a cylindrical microstrip antenna excited by a probe. 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 that governs the current distribution on the patch are derived. This set of equations is then solved using Galerkin's method in which the patch current is expanded in terms of a complete set of basis functions that take into account the edge singularity condition. The input impedance together with the radiation have been computed both exactly and in the small substrate thickness limit where a single mode approximation is employed.

We discovered that for thick substrates, hybrid modes are excited. Only in the case of axially symmetric modes are the TE modes decoupled from the TM modes and modes of different parity do not couple. The presence of the dielectric substrate widens the bandwidth and broadens the radiation pattern. The radiation pattern is insensitive to the substrate thickness, especially for high dielectrics. For wraparound antennae, all current modes with no axial variation tend to weakly radiate and, consequently, have narrow bandwidth. When the TE_{01} mode is excited, the wraparound antenna works as a good antenna. The rectangular-cylindrical patch is, on the other hand, generally, less radiating than the wraparound.

A rigorous analysis of the resonant frequency problem of both the cylindrical-rectangular and the wraparound microstrip structures is carried out using two different approaches: integral equation formulation and a perturbational approach. By using Galerkin's method in solving the integral equations, the complex frequencies are studied with sinusoidal basis functions. The effect of the edge singularity of the patch current on the convergence is investigated. Numerical results show that the HE_{10} mode for the wraparound patch and the cylindrical-rectangular patches have narrow bandwidth and, thus, are more appropriate for resonator applications. The TE_{01} and HE_{01} modes of the wraparound and cylindrical-rectangular patches, respectively, have wide bandwidth and are efficient radiating modes.

The wave propagation along microstrip lines on uniaxially anisotropic substrates having their width periodically modulated is investigated by dividing the structure into consecutive uniform sections. A rigorous formulation for calculating the capacitance matrix of uniform lines is derived. A quasi-TEM approximation is then used to obtain the circuit parameters for each section. The transfer matrix is applied to obtain the dispersion relation of the periodic structures. The effects of the anisotropy of substrate material and the strip line geometry on the stopband characteristics are exploited. The properties of two coupled width-modulated lines are also investigated.

A rigorous dyadic Green's function formulation in the spectral domain is used to study the dispersion characteristics of signal strip lines in the presence of metallic crossing strips. A set of coupled vector integral equations for the current distribution on the conductors is derived. Galerkin's method is then applied to derive the matrix eigenvalue equation for the propagation constant.

The effects of the structure dimensions on the passband and stopband characteristics have been studied. For crossing strips of finite length, the stopband is mainly affected by the period, the crossing strip length, and the separation between the signal and the crossing strips. For crossing strips of infinite length carrying travelling waves, attenuation along the signal line exists over the whole frequency range of operation.

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

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1.6 High-Speed Integrated Circuit Interconnects

Sponsor

Digital Equipment Corporation

Project Staff

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A new method for analyzing frequency-dependent transmission line systems with nonlinear terminations is developed by using the generalized scattering matrix formulation for the time domain iteration scheme. Previous works have employed either the admittance matrix, which results in extended impulse responses, or introduced artificial matching networks, which could render the solution unstable. In contrast, the generalized scattering matrix approach is most closely tied to the concept of waves. Therefore, this approach achieves a shorter impulse response that leads to a smaller computer memory requirement and faster computation time.

We have carried out the detailed procedure for solving this kind of nonlinear transient problem for a microstrip transmission line with linear source resistance. The diode-like terminal characteristics has been considered, and the speed of convergence is quite satisfactory.

Time-Domain Finite-Difference modeling has been applied to obtain propagation characteristics of microstrip structures. Maxwell equations are expressed in finite-difference form, and the substrates are considered to be anisotropic in general. Positioning the components of the electric and magnetic fields at different positions and evaluating them at alternate time steps, we obtain the components of Maxwell's equations. Boundary condition implementation is an important issue in this method. Electric and magnetic walls can be implemented simply by setting the appropriate field components zero. Open-end termination is simulated by using the open-circuit, short-circuit technique, to cancel out the reflected waves. We have used this method to illustrate graphically the field propagation along an open microstrip line. Field components are plotted in both space and time domains. The dispersive behaviour of the wave propagation can be observed. It should be noted that this method can be conveniently applied to obtain frequency-dependent characteristics of various microstrip structures such as effective permittivity, characteristic impedance, scattering matrix elements, and equivalent circuit components. An improved source plane implementation based on magnetic wall is applied for better modeling of the matched source. This method is very powerful in obtaining both the time-domain and the frequency-domain characteristics of microstrip lines, discontinuities, and coupled lines.

We are developing general purpose finite difference time domain (FDTD) algorithms to solve electromagnetic wave propagation in integrated circuit problems, in particular the discontinuities such as bends and corners. The geometry is read from a file which assigns dielectric constants, permeability, and conductivity to each discrete mesh point. To limit the domain of computation, an absorbing boundary condition has been implemented that simulates an outward propagating wave on the faces of the mesh, thus eliminating reflection from these faces. Specific problems simulated so far include two-dimensional propagation from a point source to demonstrate the effectiveness of the absorbing boundary condition and three-dimensional propagation around a 90-degree microstrip corner.

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

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

In microelectronic packaging, a problem of practical interest is the study of propagation characteristics of a shielded microstrip line in the presence of crossing strips in a multilayered structure. We have investigated the dispersion characteristics of strip lines crossed by metallic strips and embedded in the same isotropic layer and bounded by two conducting planes. A rigorous dyadic Green's function formulation in the spectral domain is used and a set of coupled vector integral equations for the current distribution on the conductors is derived. Galerkin's method is then applied to derive the matrix eigenvalue equation for the propagation constant. The dispersion properties of the signal lines are studied for both cases of finite and infinite length crossing strips.

The effects of the structure dimensions on the passband and stopband characteristics are analyzed. For crossing strips of finite length, the stopband is mainly affected by the period, the crossing strip length, and the separation between the signal and the crossing strips. For crossing strips of infinite length carrying travelling waves, attenuation along the signal line exists over the whole frequency range of operation.

Also considered are microstrip lines together with a set of the crossing strips to be placed at two different interfaces of a three-layer medium bounded by two parallel conducting plates. The crossing strips are assumed to be periodic and the three layers to be uniaxially anisotropic. The network analytical method of electromagnetic fields is applied to the hybrid-mode analysis of the frequency dependent characteristics of the structure. The transverse fields in each region are expressed by their Fourier transform in the transversal-direction and a Floquet harmonic representation in the longitudinal-direction. Using Maxwell's equations and applying boundary conditions, we obtain a set of coupled integral equations for the current distributions on the microstrip line and the crossing metallic strips. The determinantal equation for the dispersion relation can be derived by applying Galerkin's procedure to the derived set of coupled integral equations. The Brillouin diagrams are obtained numerically by seeking the roots of the obtained eigenvalue equation. The stop-band properties are numerically obtained as a function of the spacing, length, and width of the crossing metallic strips. The effects of the material anisotropy and geometrical parameters are also studied.

Publications

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