Section 3 Electromagnetics

Chapter 1 Electromagnetic Wave Theory and Applications

Chapter 1. Electromagnetic Wave Theory and Applications

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1.1 Remote Sensing of Earth Terrain

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In this project, we are investigating the theory of polarimetric passive remote sensing of wind-generated sea surfaces with potential application to ocean surface winds. The small perturbation method (SPM), derived to second order, is applied to the Stokes vectors of the thermal emission from random rough dielectric surfaces described by anisotropic directional spectra. To verify the accuracy of the SPM, a Monte Carlo simulation is performed to calculate the Stokes vectors of the emission from the simulated one-dimensional random rough surfaces with a power-law spectrum for various observation angles and surface parameters. The theoretical results of the SPM for all four Stokes parameters are in excellent agreement with the numerical results obtained from the Monte Carlo simulation. The SPM is then applied to small-scale sea surface described by an empirical surface spectrum. The results indicate that polarimetric radiometry allows us to measure wind vector with only one azimuthal observation angle. This is made possible by the different azimuthal dependence between the third Stokes parameter and the first two Stokes parameters. Radiometers with a single-azimuth-observation design will not only simplify the antenna-beam-scanning mechanism, but will also be free from the complexity associated with the data co-registration required for multiple-azimuth-observation designs.

A numerical study of the polarimetric thermal emission from ocean surfaces randomly rough in one dimension using a Monte Carlo technique is carried out. A set of finite length surface profiles with desired statistics was generated using a spectral method. Each surface was extended periodically to create an infinite rough surface, and the thermal emission was computed using the extended boundary condition method (EBC) and the method of moments (MOM). The results from the set of surfaces were then averaged to obtain the Monte Carlo estimate of polarimetric thermal emission. The surface statistics chosen were intended to model a wind perturbed ocean surface in the X to K_u band microwave region. The results of the study show that the third Stokes parameter, U_B, is sensitive to the azimuthal angle between the surface periodicity and the looking angle, the rms height of the surface, and the surface power law spectrum slope, and that this parameter is insensitive to variations in polar angle, permittivity, and surface spectrum high frequency content.

Experimental results and theoretical calculations are presented to study the polarimetric emission from water surfaces with directional features. It is observed that the measured Stokes parameters of corrugated fiberglass-covered water surfaces are functions of azimuth angles and agree very well with theoretical calculations. The theory, after being verified using experimental data, was then used to calculate the Stokes parameters of periodic surfaces without fiberglass surface layer and with rms height of the order of wind-generated water ripples. The magnitudes of the azimuthal variation of the calculated emissivities at horizontal and vertical polarizations corresponding to the first two Stokes parameters are found to be comparable to the values measured by airborne radiometer and SSM/I. In addition, the third Stokes parameter not shown in the literature is seen to have approximately twice the magnitude of the azimuth variation of either T_h or T_v. The results indicate that passive polarimetry is a potential tool in the remote sensing of ocean wind vector.

To interpret the polarimetric active remote sensing data of saline ice, we have developed a random medium model using the radiative transfer theory. The ice layer is described as a host ice medium embedded with randomly distributed inhomogeneities, and the underlying sea water is considered to be a homogeneous halfspace. The random medium model is characterized by a correlation function described by correlation lengths in both the horizontal and vertical directions. Multiple scattering effects are accounted for by solving the radiative transfer equations numerically. The effects of random roughness at the air-ice and ice-water interfaces are accounted for by modifying the boundary conditions in the radiative transfer equations. Analysis of the model for reconstruction of sea ice parameters is made. An optimization approach is used for inversion. The discrepancy between the data and the results of the forward model is minimized by changing the inversion parameters according to a nonlinear programming scheme. Reconstruction of correlation lengths in the horizontal and vertical dimensions has been accomplished using the polarimetric backscattering coefficients at different angles of incidence as input data. Effects of data diversity and noise on the reconstruction of the physical parameters of sea ice from the backscattering coefficients are being investigated.

Vegetation canopy can be modeled as either a mixture of multiple-species discrete scatterers described by a certain size, shape, and orientation distributions, or a continuous random medium characterized by correlation functions. A layer model is developed and applied to interpret radar backscattering coefficients at 5.3 GHz for a soybean canopy. The canopy is modeled as a random medium containing spheroidal scatterers for the leaves. The data were taken over an extended time period from the early to late stages of vegetation. The theoretical results and the experimental data are in good agreement. The lateral correlation length is observed to be highly correlated with the canopy fractional volume. With consideration of the interrelations among biophysical parameters, the model is then used to simulate backscattering coefficients under various conditions. The results provide sensitivity domains of radar responses to soil moisture and vegetation biomass for inversion assessment. Furthermore, the polarization signatures of the vegetation canopy are synthesized to illustrate structural information conveyed by polarimetric data.

1.2 Electromagnetic Waves in Multilayer Media

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The electromagnetic radiation from a VLSI chip package and heatsink structure is analyzed by means of the finite-difference time-domain (FDTD) technique. The dimensions of a typical configuration calls for a multizone gridding scheme in the FDTD algorithm to accommodate fine grid cells in the vicinity of the heatsink and package cavity and sparse gridding in the remainder of the computational domain. The issues pertaining to the effects of the heatsink in influencing the overall radiating capacity of the configuration are addressed. Analyses are facilitated by using simplified heatsink models and by using dipole elements as sources of electromagnetic energy to model the VLSI chip. The potential for enhancement of spurious emissions by the heatsink structure is illustrated. For heatsinks of typical dimensions, resonance is possible within the low gigahertz frequency range. The exploitation of the heatsink as an emissions shield by appropriate implementation schemes is discussed and evaluated.

The use of equipment enclosures to shield against emissions and external energy is a common practice. Efforts range from metal impregnated plastics to thick steel panels incorporating waveguide design in air vents. The choice of complexity depends on system performance and application. The question has often been raised as to whether high field intensities within such enclosures will affect equipment performance. Clearly, this is increasingly pertinent in cases of heavy shielding where resonator-like structures with high quality factors result. Moreover, in these cases, any energy leakage may be highly frequency selective with substantial associated field strength. The primary motivation for studying such structures is that computers are now operating at faster speeds and consuming more power, resulting in significantly increased levels of power at higher frequencies. The finite-difference time-domain (FD-TD) technique is used in analyzing this problem and the metrics are total radiated power and field patterns within the enclosure. The excitation sources are a line current source for the two-dimensional models and dipoles for the three-dimensional cases. A Gaussian amplitude is assumed in order to obtain multifrequency characteristics and to exhibit the resonance properties of the model. In addition to the radiated power through the apertures, the power absorbed in the resistive material is also calculated.

In high-speed digital circuits, high frequency phenomena affects the characteristics of the interconnections. Physical discontinuities or non-uniformities in the connections may cause severe reflections when they no longer act like conducting wires, but behave like transmission lines and/or waveguides. In multilayered digital circuits, vias constitute one of the most commonly-used class of interconnects. Vias are not good carriers of high-speed signals because they cause signal distortion and reflections as well as severe degradation in the high frequency components. Previously, analysis and modeling of a single via and some quasi-static or quasi-TEM analyses of single via configurations have been carried out.

To date, analysis of coupled noise between adjacent vias has received very little attention. This is mainly because of the complexity of multi-via structures and the difficulty of modeling and analyzing them accurately over a broad frequency range. The electromagnetic coupling between two adjacent vias in a multilayered integrated circuit is analyzed by means of equivalent magnetic frill array models incorporated with the even- and odd-mode approach. Closed-form expressions for the coupled noise on the passive via are derived. The coupling responses in the frequency domain and crosstalk waveforms in the time domain for some multilayered via structures are calculated based on these formulas. A four-layer experimental model is constructed, and measurements are taken for the transmission, reflection, and coupling responses.

Measurements show good agreement with calculated results over a frequency range of up to 18 GHz.

1.3 Simulation of Electromagnetic Wave Scattering

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This is a long-term project for the development of a comprehensive theoretical model for computer simulation of three-dimensional micro- and millimeter wave scattering and emission phenomena. Our major tasks include (1) a simulation program—development of a baseline simulation that includes the effect of environment, hard targets, atmospheric absorption and scattering, and ground reflection; (2) validation and documentation—generation of a synthetic scene for comparison with real data and production of user manuals and validation reports; and (3) upgrade assessment—studies of models that can be added to the baseline simulation and various ways to integrate the models.

Our immediate goals in this research project are to (1) assemble any physical models available that satisfy the minimum requirements defined above and (2) build a preliminary simulation package using these models. The simulation package should demonstrate the process of generating scenes from standard input data sets and the possibility of direct or indirect comparison with recorded images.

We have developed a baseline simulation package with X-window/Motif graphical user interface. This program (1) first accesses the GIS feature map and elevation map and creates displays of them, (2) allows a user to identify and highlight particular terrain features in the map region from a menu, and (3) interfaces with the background terrain scattering coefficient database created by the EMSARS program and the clutter statistics model to generate simulated radar images. A simple terrain shadowing effect is included. The current database is created using the random medium volume scattering model and composite rough surface scattering model.

1.3.1 Publications

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1.4 Superconducting Transmission Lines

1.4.1 Simulations of Vortices in Arrays of Josephson Junctions

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Project Staff

Joel R. Phillips, Dr. Herre S.J. van der Zant, Robert D. Bock, Professor Terry P. Orlando, Professor Jacob K. White

Vortices play a central role in determining the static and dynamic properties of two-dimensional (2D) superconductors. Artificially fabricated networks of superconducting islands weakly coupled by Josephson junctions are model systems to study the behavior of vortices. Studies of vortices in Josephson junction arrays generally neglect the magnetic fields induced by currents flowing in the array; i.e., it is assumed that the penetration depth for flux λ is much larger than the size of the array. With the present niobium technology, arrays have been made with λ of the order of the cell size; therefore, effect of induced fields must be considered for an accurate description of these systems.

We use numerical simulation to investigate how a variety of static vortex properties are affected by finite penetration depth λ, and we calculate for the first time the self-consistent current and magnetic fields from a vortex in a 2D array. We find that to calculate the correct current and field distributions, we must include nearly all mutual inductance terms to account for the full 3D behavior of the magnetic fields. However, to calculate the energy barrier for cell to cell vortex motion, which was first shown by Lobb, Abraham, and Tinkham (LAT) to be 0.2 E_J, where E_J is the Josephson coupling energy, including only self and nearest neighbor inductance's is sufficient. The LAT calculation neglected the presence of induced magnetic fields. We show that induced fields may increase the energy barrier substantially above 0.2 E_J. Our calculations also show that the thermodynamic lower critical field of the array is enhanced when the computation self-consistently accounts for induced magnetic fields and that by using only a self-inductance term to model the induced fields, the lower critical field is overestimated.

There has been much recent interest in the properties of Josephson-junction arrays driven by DC and AC currents, particularly in the study of fractional and subharmonic Shapiro step structure. While the occurrence of fractional steps in a magnetic field seems to be explained by a phenomenological model of a moving vortex superlattice, the origin of subharmonic structure, particularly in zero applied field, is less clear. Several explanations have been proposed, including inductive (self-field) effects. There has also been long-standing interest in the use of Josephson arrays as coherent microwave sources, and recently the first observation of coherent emission from 2D Josephson-junction arrays was reported. The arrays used in the experiments had high critical currents, indicating that the strength of the magnetic fields induced in these arrays by circulating supercurrents is fairly large. However, there have been relatively few dynamic studies of Josephson arrays that consider the effect of induced magnetic fields; and most of the previous treatments have severely approximated the form of the induced fields.

We have made dynamic simulations of 2D Josephson arrays where inductive effects are important. We have included the mutual inductance interactions between all cell pairs in the arrays when necessary to calculate the correct screening properties of the induced field. We find that induced magnetic fields can produce subharmonic Shapiro step structure in zero applied magnetic field, and we have developed a qualitative description of the movement of vortices on the subharmonic Shapiro steps. Although the symmetry-breaking effect of the self-fields can generate subharmonic Shapiro steps, the steps do not appear to be due to the formation of an induced commensurate vortex state at the edges of the array. Another effect of the self-fields is that in arrays with penetration depths small relative to the size of the array, the screening effects due to induced fields may be strong enough to destroy phase-locking over some parameter range, significantly reducing the width of the giant Shapiro steps. Thus, for coherent emission from 2-D arrays, self-field effects must be reduced.

1.4.2 Superconducting Transmission Lines

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Project Staff

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A full-wave spectral-domain volume-integral-equation method has been developed to analyze various configurations of superconducting transmission lines: microstrip lines, striplines, coplanar strips, and coplanar waveguides. In the formulation, a spectral-domain Green's function for isotropic, layered media is used to set up an integral equation for the electric field inside the superconducting strips. Galerkin's method with roof-top basis functions is employed to solve for the complex propagation constant and current distribution. The characteristic impedance of the structures is then obtained from transmission line theory. This method rigorously accounts for the anisotropy and the finite thickness of the superconducting films, yielding accurate characterization for the loss and kinetic effect of the superconductors. However, this technique is computationally inefficient.

To implement an efficient method, an equivalent surface impedance is used to transform the superconducting strip with finite thickness to an infinitely thin strip. This equivalent surface impedance accounts for the loss and kinetic inductance of the superconductors. An empirical formula for the current distribution in a thin superconducting film is determined for the derivation of the equivalent surface impedance. To include effects of anisotropic substrates, a 2-D dyadic Green's function for anisotropic, layered media is used to formulate an integral equation for the surface current. Galerkin's method with entire-domain basis functions is used to solve for the complex propagation constant and the surface current. The characteristic impedance is then calculated using the power-current definition. This method has been used to analyze superconducting single and coupled microstrip lines on anisotropic substrates.

A closed-form expression was found for the current distribution in an isolated strip made from a superconducting thin film with thickness less than a few penetration depths. This equation gives a good approximation within certain limits for the resistance and inductance per unit length of superconducting striplines and microstrip lines. Both the ac resistance of an isolated superconducting strip and the resistance per unit length of a superconducting stripline calculated using this closed-form expression agree well with the numerical results generated by the modified Weeks' method. The possibility now exists of using this expression along with the integral equation method to develop an efficient full-wave method for analyzing superconducting planar transmission lines.

1.4.3 Discrete Superconducting Vortex Flow Transistors

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Vortex Flow transistors (VFT) are of renewed interest after a discrete flux-flow device made of weak links in a high-temperature film has demonstrated promising results. Current gains higher than one, transresistances of the order of 10 Ω, a maximum output voltage of about 20 mV, and speeds of the order of 50 ps were obtained. Flux-flow devices were proposed more than 10 years ago and were fabricated in a long continuous Josephson junction. There are two versions of a

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VFT in long Josephson junctions; one is a device made of a long overdamped junction (the McCumber parameter $\beta_c < 1$) and the other is made with an underdamped junction ($\beta_c > 1$). The disadvantages of long Josephson junctions are that the output resistance is low (much smaller than 1 Ω) and that the output voltage is generally much smaller than 1 mV. Moreover, it is difficult to manipulate the parameters and improve the response time of the device. Discrete vortex flow transistors (DVFT) overcome these difficulties.

Vortex Flow Transistors (VFT) are three-terminal devices: a gate current regulates the number of vortices in the device and a bias current causes the vortices to move which leads to a voltage proportional to the number of vortices. A DVFT consists of a parallel array of Josephson junction which are coupled to each other by superconducting wires. Each junction is separated from its neighbor by the lattice constant p of the cell. An important parameter in discrete 1D arrays is the penetration depth Λ_J, in units of p, which is a measure of the discreteness of the system. The penetration depth Λ_J is defined as $\Lambda_J = \sqrt{L_J/L_s}$ Here, L_s is the self-inductance of a cell in the array and L_J is the Josephson inductance, $L_J = \Phi_o/(2\pi I_c)$, where Φ_o is the flux quantum and I_c is the critical current of a single junction. For $\Lambda_J < 1$, vortices are well localized objects; whereas, for $\Lambda_J >> 1$ vortices are spread out over several cells. From measurements of Fiske modes in underdamped arrays, we have determined that in our DVFT geometry, $L_s = 1.1\mu_o p$. We also have shown that for overdamped DVFTs one would like to have $\Lambda_J < 1$.

We have fabricated discrete overdamped vortex flow transistors (DVFTs) made of short niobium Josephson tunnel junctions connected in parallel. The results of our DVFT compare with the high-T_c devices and long continuous Josephson junctions. We have also done model calculations on our DVFT which are in good agreement with our experimental results. We calculated the current gain, transresistance, the output voltage and output resistance. Our model is also applicable to other 1D discrete systems and can also be used to model long Josephson junctions. Our analysis shows that, when disregarding the lower temperatures and voltage levels in low-T_c materials, DVFTs made of niobium tunnel junctions can perform at the level comparable to the present high-T_c flux-flow devices.

1.4.4 Fiske Modes in One-Dimensional Parallel Josephson-junction Arrays

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A one-dimensional array of Josephson junctions connected in parallel by superconducting wires may qualitatively be viewed as a discrete version of a single continuous Josephson junction. In a magnetic field, a continuous underdamped Josephson junction shows currents steps in the current-voltage characteristic which are known as Fiske modes. The voltage differences between adjacent Fiske-steps map out the dispersion relation for electromagnetic waves of 1D systems. In a magnetic field, the dispersion relation $\omega(k)$ is linear for a continuous system with some damping, but should bend and exhibit standing wave behavior near the Brillouin zone for a discrete system. Moreover, in discrete arrays the flux through one cell couples to neighboring cells through the mutual inductances. This effect is generally neglected in long Josephson junctions where the magnetic field is assumed to be only parallel to the junction surface.

In arrays, the discreteness parameter is defined as the ratio of the Josephson inductance L_J to the self-inductance of the individual loops L_s. The square root of the discreteness parameter is the penetration depth (Λ_J) for 1D discrete system expressed in units of the latttice spacing, $\Lambda_J = \sqrt{L_J/L_s}$. For $\Lambda_J > 1$, vortices extend over several array cells and the phase of the vortices can be approximated by a sinusoidal wave. This is the linear regime where for a long continuous Josephson junction the Fiske mode analysis has been done. There has not been a systematic analysis of discrete arrays in this linear regime. In the linear regime long Josephson junctions may be used as flux-flow oscillators and paramteric amplifiers in the millimeter and sub-millimeter wave range.

We have studied resonances in underdamped, discrete one-dimensional Josephson junction arrays with $\Lambda_J^2 >> 1$, so that a linear approximation can be used. We have shown that in general the position of the resonances is determined by the dispersion relation of a transmission line of inductors L_s connected in parallel with capacitors C alone, which replace the Josephson junctions. In calculating the dispersion relation, we have taken into account the inductances between adjacent cells L_{nn} and observed good agreement with the experimental data. Consequently, from measuring the voltages where the steps occur, one can construct the dispersion relation of the 1D discrete system. We have also measured resonances in a 1D array where the primitive cell consists of two different lattice cells. We have observed an acoustic branch in the dispersion relation for low frequencies and an optical branch for higher frequencies which are in agreement with numerical simulations of the full dynamics.

Our Fiske mode analysis on 1D arrays may also be important from a more applied point of view. With current injected at one of the edges of a 1D array, the array critical current varies linearly with applied field and the slope in this region depends on Λ_J and L_{nn}/L_s. From measuring Fiske modes in a 1D array, one can obtain L_{nn}/L_s and L_sC so that this critical current measurement yields L_s (L_J is known because the junction critical current is known) which in turn yields the junction capacitance. Note, that in this procedure all quantities are measured and that no additional information about the barrier or the dielectrics is needed. We have used this method to determine the specific junction capacitance as a function of the critical current density for the PARTS process. Moreover, the array critical current as a function of applied field determines the current gain of a discrete vortex flow transistor and mutual inductance effects can be taken into account through L_{nn}/L_s. Thus, a good understanding of the dynamics of 1D arrays with inclusion of mutual inductances can be used to determine circuit parameters accurately which is essential when designing SFQ devices and circuits with discrete vortex flow transistors.

1.4.5 Publications

Berman, D., H.S.J. van der Zant, T.P. Orlando, and K.A. Delin. "Discrete Vortex Flow Transistors." Submitted to *Phys. Rev. B.*

Bock, R.D., J.R. Phillips, H.S.J. van der Zant, and T.P. Orlando. "Influence of Induced Magnetic Fields on the Static Properties of One-dimensional Parallel Josephson-junction Arrays." *Phys. Rev. B.* Forthcoming.

José, J.V., G. Ramirez-Santiago, and H.S.J. van der Zant. "Critical Exponents of Frustrated Josephson-junction Arrays." *Proceedings of the 20th International Conference on Low Temperature Physics (LT20),* Eugene, Oregon, August 1993.

Lee, L.H., W.G. Lyons, T.P. Orlando, S.M. Ali, and R.S. Withers. "Full-Wave Analysis of Superconducting Microstrip Lines on Anisotropic Substrates using Equivalent Surface Impedance Approach." *IEEE Trans. Microwave Theory Tech.* 41(12): 2359-2367 (1993).

Lee, L.H., T.P. Orlando, and W.G. Lyons. "Current Distribution in Superconducting Thin-Film Strips." *IEEE Trans. Appl. Superconductivity.* Forthcoming.

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