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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Polarimetric radar calibration algorithms using a combination of point targets and reciprocal distributed targets are developed. From a distributed target, a matrix equation is derived which can be converted into an equivalent point target response. The equivalent point target corresponds physically to a 90-degree polarization rotator which is non-

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reciprocal and rotation-invariant. Due to this equivalent-point-target interpretation, the cases of polarimetric calibration using two point targets and one distributed target then reduce to those using three point targets, which have been solved in previous research. Regarding the calibration using one point target and one reciprocal distributed target, two cases are analyzed with the point target being a sphere (trihedral reflector) or a polarimetric active radar calibrator (PARC). For both cases, the general solutions of system distortion matrices are written as a product of a particular solution and a matrix with one free parameter, and then an additional assumption about the distributed target is made to determine the free parameter. For the trihedral-reflector case, when the particular solution is applied for calibration, the measured polarimetric data can be calibrated to the level that only rotation errors remain. When azimuthal symmetry is assumed for the distributed target, an iterative scheme is devised to solve the rotation parameter. For the PARC case, the residual error is similar to the channel imbalance after the data are calibrated by the particular solution, and the free parameter can be determined by knowing one ratio of two covariance matrix elements of the distributed target. Numerical results were simulated to demonstrate the validity of the algorithms developed.

A branching model is proposed for the remote sensing of vegetation. The frequency and angular responses of a two-scale cylinder cluster are calculated to demonstrate the significance of vegetation architecture. The results indicate that it is necessary for theoretical models to take into account the architecture of vegetation which plays an important role in determining the observed coherent effects. A two-scale branching model is implemented for soybean with its internal structure and the resulting clustering effects considered. Furthermore, at the scale of soybean fields, the relative location of soybean plants is described by a pair of distribution functions. The polarimetric backscattering coefficients are obtained in terms of the scattering properties of soybean plants and the pair distribution function. Theoretical backscattering coefficients evaluated using the hole-correction pair distribution are in good agreement with extensive data collected from soybean fields. Compared with the independent-scatterer pair distribution, it is found that the hole-correction approximation, which prevents two soybean plants from overlapping each other, is more realistic and improves the agreement between the model calculation and experimental data near normal incidence. Extension to a multi-scale branching model can be achieved by recursion.

Fully polarimetric scattering of electromagnetic waves from snow and ice is studied with a multi-layered random medium model and applied to interpret experimental data obtained under laboratory controlled conditions such as CRRELEX. The snow layer is modeled as an isotropic random medium. The sea ice is described as an anisotropic random medium due to the nonspherical shape of brine inclusions. The underlying sea water is considered as a homogeneous half-space. The random media in both layers are characterized by three-dimensional correlation functions with variances and correlation lengths corresponding to the fluctuation strengths and the physical geometries of the inhomogeneities, respectively. The strong fluctuation theory is used to calculate the effective permittivities of the random media. The distorted Born approximation is then employed to obtain the covariance matrix which represents the fully polarimetric scattering properties of the snow-ice media. It has been shown that the polarimetric covariance matrix contains more information than the conventional scattering coefficients on the remotely sensed media.

In a saline ice sheet under quiescent condition, the background ice grows in columnar form and saline water is trapped between ice platelets in the form of brine inclusions which are usually ellipsoidal. The ice tends to grow vertically downward rendering the ellipsoidal inclusions aligned preferably in the vertical direction and the crystallographic C axes parallel to the horizontal plane. In this case, the C axes are, however, random in the azimuthal direction. The strong fluctuation theory is extended to account for vertically aligned ellipsoidal brine inclusions with C axes randomly oriented in the horizontal direction. The brine inclusions are described by three-dimensional local correlation functions. The configuration average over the azimuthal orientation angles is carried out in the process of deriving the global correlation tensor. The distorted Born approximation is applied to obtain the covariance matrix for the multilayered snow-ice configuration. The theoretical results show non-zero cross-polarized returns under the first-order distorted Born approximation. We have also compared the results with experimental data obtained by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL).

A multivariate K-distribution has been developed to model the statistics of fully polarimetric radar 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; N obeys the negative binomial distribution with a parameter α and mean $\bar{N}$. Subsequently, an n-dimensional K-distribution, with either zero or nonzero mean, is developed in the limit of infinite $\bar{N}$ or 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. The above model is well supported by experimental data provided by MIT Lincoln Laboratory and the Jet Propulsion Laboratory in the form of polarimetric measurements. The results are illustrated by comparing the higher-order normalized intensity moments and cumulative density functions (CDF) of the experimental data with theoretical results of the K-distribution.

Among the various theoretical models applied to study the electromagnetic wave scatterings from geophysical terrain, such as snow and ice, the radiative transfer theory has drawn intensive attention in the microwave remote sensing community during the past years. In most of the scattering models, the volume scattering and the surface scattering effects have been investigated separately. Recently, there has been a growing interest in the construction of composite models which can take into account both types of scattering. We derived the first order iterative solution to the vector radiative transfer equations for a two-layer medium with a diffuse top boundary and an irregular bottom boundary of Gaussian roughness. The Kirchhoff approximation and the geometrical optics approach with shadowing correction are used in formulating the boundary conditions. To demonstrate the utilities of the theory, randomly oriented spheroidal discrete scatterer model is used to calculate the backscattering coefficients from a soybean field in different growing stages and then compared to the experimental measurements. Good agreement has been achieved for both the co-polarized and the cross-polarized data. It is observed that the presence of the rough surface can significantly enhance the backscattering at small incident angles and increase the cross-polarized returns. The polarization signatures calculated based on the Mueller matrix show a straight distortion track and an observable pedestal. Numerical comparison to the backscattering coefficients calculated by using planar bottom boundary conditions with or without the incoherent addition of the rough surface effects are also made.

The concept of polarimetry in active remote sensing is extended to passive remote sensing. The potential use of the third and fourth Stokes parameters U and V, which play an important role in polarimetric active remote sensing, is demonstrated for passive remote sensing. It is shown that, by the use of the reciprocity principle, the polarimetric parameters of passive remote sensing can be obtained through the solution of the associated direct scattering problem. In particular, the full polarimetric information, including the corresponding brightness temperatures of U and V, can be obtained from the solution of the direct scattering problem for four different polarizations of the incident wave. These ideas are applied to study polarimetric passive remote sensing of periodic surfaces. The solution of the direct scattering problem is obtained by an integral equation formulation. Incidence on a penetrable, lossy medium is considered. Since the kernels of the integral equations are the periodic Green's functions and their normal derivatives on the surface, rapid evaluation of the slowly convergent series associated with these functions is critical for the method to be feasible. The study has shown that the brightness temperature of the Stokes parameter U can be significant in passive remote sensing. Values as high as 50 K are observed for certain configurations.

To demonstrate the use of polarimetry in passive remote sensing of azimuthally asymmetric features on a terrain surface, an experiment was designed and implemented. A triangular corrugation pattern was made on the sandy soil surface. Polarimetric brightness temperatures are measured with horizontal, vertical, and 45° polarization orientations for various observation angles. From the measured temperatures, absolute values as high as 30-40 K of the third Stokes brightness temperatures are observed. A theoretical analysis of the data indicates that the high values of U are caused by the azimuthal asymmetry on the remotely sensed soil surface. It is also observed from the experiment that the brightness temperatures for all three Stokes parameters vary as the observation direction varies from being parallel to the surface row structure to being perpendicular to the row structure. The significant implication of this experiment is that the surface asymmetry can be detected with a measurement of U at a single azimuthal angle.

1.2 Electromagnetic Waves in Multilayer Media

Sponsors

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Recent studies on electromagnetic emissions have identified the significance of resonance in the radiation and re-radiation of printed wiring board (PWB) components such as transmission lines and heatsinks. This has drawn attention to other components within a computer system which are of larger dimensions and which are likely candidates to resonate within the frequency range of emissions tests. An arrangement in computer systems which falls into this category is the modules-on-backplane configuration. Discussions with DEC engineers have identified the voltage fluctuations across the relatively high impedance reference connections, between a reference plane within a module and that on the backplane, as a likely energy source for electromagnetic emissions. The array arrangement of multiple modules on a backplane raises the possibility of parallel plate resonances where the resonance frequencies, to leading order, are inversely proportional to the dimensions of the module planes. The large dimensions of the module planes relative to the signal etch runs, heatsink dimensions, etc., imply that any resonance effects may be manifested at lower frequencies.

There is common perception that in the printed wiring board (PWB) environment stripline configurations will generate lower emission levels than microstrip structures. In previous years, the radiation properties of both microstrip and stripline structures of finite size were quantitatively compared. The examination of conducting structures which may model shielding enclosures on the radiating properties of the two structures is of interest, as these configurations correspond to the case where modules are placed in close proximity to the shielding enclosure common in computer systems.

Metallic enclosures are commonly used to house computer systems. The electromagnetic field distribution and intensities which result from sources within the enclosure are of concern because of the possibility of strong fields existing due to the resonator structure formed by the metallic enclosure. The effects of adding resistive material of varying dimensions, resistivities, and positions to the enclosure is also examined. The study will attempt to determine the optimum parameters for the resistive material which will minimize the electromagnetic field intensity within the enclosure. Perforations (holes, slots) in the metallic enclosure and the corresponding radiated power are also considered.

For each configuration, field strengths, radiated power levels, and resonance frequencies (which are crucial for the radiation mechanism) are being investigated. This study will benefit the design of integrated circuit interconnections to meet regulatory limits on electromagnetic emission levels. It reflects the progression from examining module interconnect and component radiation in relative isolation (performed in the last two contract years) to more realistic situations which incorporate interaction with other conducting structures in close proximity, as is the case at the system level.

The finite difference-time domain (FD-TD) technique is applied to the solution of Maxwell's equations. A computer program, which can be used to simulate and study numerous electromagnetic phenomena, is developed and implemented on an IBM 386-compatible personal computer. The FD-TD technique is a useful tool for students in electromagnetics. The technique is flexible and can be applied to many basic EM scattering and radiation problems. Because field solutions are found as a function of time, visualization of the propagation of the EM fields is possible. The FD-TD technique is implemented for a two-dimensional rectangular grid in conjunction with a second-order absorbing boundary condition. Both E- and H-field polarizations are analyzed. Finite objects consisting of dielectric, magnetic and conducting materials, and perfectly conducting infinite ground planes are modeled. Plane wave and line current sources are implemented. In addition to the capability of animating the propagation of the EM fields, radiation and scattering patterns can be generated.

A methodology developed to handle dispersive materials in the time domain is extended to model the dispersive characteristics of the impedance boundary condition used for a thin layer coating over perfect conductors. The impedance boundary condition is first approximated as a rational function of frequency. This rational function is then transformed to a time domain equation, resulting in a partial differential equation in space and time. Discretization of the time domain model to efficiently handle the thin layer coating is presented in the context of the finite-difference time-domain (FD-TD) technique. The methodology is verified by solving a one-dimensional problem using the FD-TD technique and comparing it with the analytical results.

1.3 Aircraft Landing Systems: ILS, MLS, GPS, and SVS

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Precision landing system plays an important role in continuing air travel services during adverse weather conditions. Instrument Landing System (ILS) has been in service for the past five decades, and microwave landing system (MLS) will be gradually replacing ILS within the next decade. These two systems require ground equipments to work properly; therefore, their usage is limited to where such setup is available. Two alternative technologies that do not require ground setups have been proposed as the future replacement for ILS and MLS: the synthetic vision (SV) sensors and the global positioning system (GPS).

In this project we have developed a computer simulation tool EMSALS which uses the databases of navigational and commercial radiowave transmitters to calculate the strengths of desired and undesired signals, and generates an EM interference assessment based on user-selected assumptions. The first part of the software EMSALS/I (for ILS) has been used to analyze the frequency congestion and electromagnetic interference problems in the continental United States given the assumptions of the current FAA standard interference protections. Emphasis was first placed on ten complex metropolitan areas with high densities of runways. Then the less densely populated regions were analyzed to determine ILS capacity across the entire continental United States (CONUS).

The second part of the software, EMSALS/M (for MLS), was used to evaluate channel availability and to generate a frequency assignment plan given the assumptions of the current ICAO MLS channel assignment rules and interference protection standards. The channel assignments had to be carried out for ILS-to-MLS conversion sites as well as new candidates, including heliports which cannot be sited with ILS. The total number of candidate sites is over 1800.

The instrument landing system (ILS) is the standard precision landing aid used by thousands of airline carriers and general aviation aircraft. In recent years, there have been growing concerns over potential hazzards from FM-broadcast interference. The ILS localizer, which provides lateral guidance during the aircraft landing phase, has its frequency band (108-112 MHz) located right above the commercial FM-broadcasting stations (88-108 MHz). Because the effective radiated power of a localizer transmitter is typically around 15 W, as compared to 10-100 kW for an FM station, it is possible for FM signals to overload the airborne receiver front-end or to drive it out of specifications and cause intermodulation interference.

We developed a scheme to link the interference immunity with the risk allowance for instrument landing operations. The risk allowance is derived as a function of the aircraft position. By the very nature of landing, the allowable risk from interference decreases or becomes more stringent as the aircraft approach the decision height. We also establish the composite probability of interference from the statistical models of systems involved, including the localizer transmitter power, FM station power, propagation factors, antenna directivity, and variations in airborne receivers. By comparing the composite probability of interference with the risk allowance at each point within the service volume of ILS localizer, we can then determine whether there is harmful interference from the FM stations. A computer program has been developed for the model.

Electromagnetic interference is one of the factors that can adversely affect GPS receiver functioning during the critical phase of final approach and landing. Although no actual incidence has been reported, in theory the threat from a moderately low power interference source does exist. In this study, we conducted experimental investigation of SPS GPS receiver susceptibility to electromagnetic interference. An aviation-grade GPS receiver mounted on the roof of a six-story building was subject to on-channel and off-channel CW and narrow-band noise with varying power levels. The interfering signal was transmitted over the open space to reach GPS antenna. We used a combination of IBM PC and receiver front-panel display to continuously record GPS data and warning flag for the cases with and without jammers. Taking the receiver front-end as the reference point, we obtained the interference power level that causes the GPS receiver to lose lock and become unable to provide accurate position data. This level is then converted to antenna receiving power, from which we estimate the effective radiation power level required for interferers at a distance.

1.4 Publications

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Yueh, S.H., J.A. Kong, and R.T. Shin. "External Calibration of Polarimetric Radars using Point and Distributed Targets." *J. Electromag. Wave Appl.* 6(7): 921-941 (1992).

Meeting Papers

Beaudoin, A., T. Le Toan, C.C. Hsu, H.C. Han, J.A. Kong, and R.T. Shin. "Simulation of Forest Backscatter as a Function of Forest and Ground Parameters." Paper presented at the International Geoscience and Remote Sensing Symposium, Houston, Texas, May 26-29, 1992.

Han, H.C., J.A. Kong, R.T. Shin, S.V. Nghiem, and R. Kwok. "Application of Theoretical Models to Active and Passive Microwave Measurements of Saline Ice." Paper presented at the International Geoscience and Remote Sensing Symposium, Houston, Texas, May 26-29, 1992.

Hsu, C.C., H.C. Han, R.T. Shin, J.A. Kong, A. Beaudoin, and T. Le Toan. "Radiative Transfer Theory for Polarimetric Remote Sensing of Pine Forest." Paper presented at the International Geoscience and Remote Sensing and Symposium, Houston, Texas, May 26-29, 1992.

Hsu, C.C., Y.E. Yang, R.T. Shin, J.A. Kong, C. Kohler, T. Nguyen, H. Nguyen, and J. Ho. "Applications of EMSARS Background Model to MMW Vegetation Scattering Simulation." Paper presented at the Ground Target Modeling and Validation (GTMV) Conference, Marquette, Michigan, August 17-19, 1992.

Kong, J.A. "Progress in Electromagnetics and Future Developments." Paper presented at the International Electromagnetic Compatibility Symposium, Singapore, December 7-9, 1992.

Kong, J.A. "Theoretical Modeling for Passive Microwave Remote Sensing of Earth Terrain." Paper presented at the URSI Specialists Meeting on Microwave Radiometry and Remote Sensing, Boulder, Colorado, January 24-26, 1992.

Kong, J.A. "Characterization of Earth Terrain Material as Random Media Applied to Remote Sensing." Paper presented at the International Electromagnetic Compatibility Symposium, Singapore, December 7-9, 1992.

Nghiem, S.V., R. Kwok, J.A. Kong, R.T. Shin, A.J. Gow, and S.A. Arcone. "Effective Permittivity of Saline Ice Under Thermal Variation." Paper presented at the International Geoscience and Remote Sensing Symposium, Houston, Texas, May 26-29, 1992.

Xia, J., and J.A. Kong. "Electromagnetic Profile Reconstruction using the Riccati Equation Approach." Paper presented at the IEEE APS

International Symposium, Chicago, Illinois, July 18-25, 1992.

Xia, J., T.M. Habashy, R.T. Shin, and J.A. Kong. "The Renormalized STIE Aproach Applied to Inversion of Soil Moisture Profiles." Paper presented at the National Radio Science Meeting, Boulder, Colorado, January 7-10, 1992.

Xia, J., and J.A. Kong. "Electromagnetic Inverse Scattering in Remote Sensing." Paper presented at the Optical Society of America Topical Meeting on Signal Recovery and Synthesis, New Orleans, Louisiana, April 14-15, 1992.

1.5 Superconducting Transmission Lines

1.5.1 Simulations of Vortices in Arrays of Josephson Junctions

Sponsors

DARPA/Consortium for Superconducting Electronics
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Project Staff

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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 for studying the behavior of vortices. These arrays have also been used to study the superconducting-insulator transition, Giant Shapiro steps, and the Kosterlitz-Thouless-Berezinskii (KTB) transition.

Studies of vortices in Josephson junction arrays generally neglect magnetic fields induced by currents flowing in the array. It is assumed that the penetration depth for flux λ is much larger than the size of the array. With the present SNAP technology, all niobium 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 vortex static 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 in order to calculate the correct current and field distributions, the full 3D behavior of the magnetic fields must be accounted for by including nearly all mutual inductance terms. 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 inductances is sufficient. The LAT calculation neglected 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. By using only a self-inductance term to model the induced fields, the lower critical field is overestimated.

Self-consistently determining the currents and fields in a Josephson junction array is a difficult numerical problem. This is because the fields induced by a junction current affect the current through every junction in the array. This dense interaction implies that for an array having N cells, on the order of N^2 words of computer memory are required just to store the mutual inductance matrix. If a direct approach is used to compute the self-consistent solution by factoring the inductance matrix, on the order of N^3 operations are required. For example, the inductance matrix of a 100 x 100 array requires more than 400 megabytes of memory to store and on the order of 10^{12} operations to factor.

To make the computation tractable, we derive a novel simulation algorithm which combines several numerical techniques with an appropriate problem formulation. When used to simulate an N-cell array, this approach reduces the storage required to order N and decrease the computation time to order N log N. This approach makes it possible to compute self-consistent array currents and fields in a 100 x 100 array in a minute or so using a scientific workstation (IBM RS6000).

1.5.2 NonLinear Effects in Superconducting Transmission Lines

Sponsors

DARPA/Consortium for Superconducting Electronics
Contract MDA972-90-C-0021

Project Staff

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The Ginzburg-Landau theory has been applied to model the nonlinear behavior of superconducting transmission lines, including striplines and microstrip lines.

The Ginzburg-Landau differential equations are solved numerically inside the signal line where high current density exists. The resulting distribution of the magnetic penetration depth and conductivity is then used to calculate the nonlinear inductance and resistance of the superconducting transmission lines. Numerical results are compared with measurements on NbN and YBCO stripline resonators. Good agreement is obtained for the nonlinear shift of resonant frequency. However, the measured Q factor appears to be much more nonlinear than predicted by the numerical model. It is believed that some other nonlinear loss mechanism is dominating over that caused by pair-breaking.

This observation motivates us to investigate the nonlinear loss caused by vortex motions. A nonlinear diffusion equation for the magnetic flux is formulated for the flux flow dynamics. Appropriate models for the nonlinear diffusion coefficient will be adopted for the numerical calculation of flux flow in a superconducting slab.

1.5.3 Superconducting Transmission Lines

Sponsor

DARPA/Consortium for Superconducting Electronics
Contract MDA972-90-C-0021

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 2D 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.

We have been successfully measuring the long wavelength infrared quantum well (LWIR) intersubband absorption in 2 to 5 μm wavelength region based on InAs/InGaAs/AlAs resonant tunneling diode structures for the IR detectors application. Over 40 percent intersubband absorption can be achieved from a doped single quantum well through our delicated designed waveguiding system, where IR is focused upon the sample edge and makes 20 times total internal reflection while it propagates along the samples and dramatically increases the absorption strength. We also demonstrate both theoretically and experimentally that TE as well as TM modes can excite the intersubband absorption. We also pointed out the interface Fe interband absorption at 0.3 eV could seriously obscure the IR absorption spectra and have shown how they can be avoided. These results, applied in concert with recently developed selective etches that allow us to make electrical contact to the quantum well directly and open the way to realizing high performance LWIR detectors.

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8 MIT Lincoln Laboratory.

1.5.4 Publications

Book Chapters

Delin, K.A., and T.P. Orlando. "Superconductivity." In *The Electrical Engineering Handbook.* Ed. R.C. Dorf. Boca Raton, Florida: CRC Press, 1993.

Published Journal Articles

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