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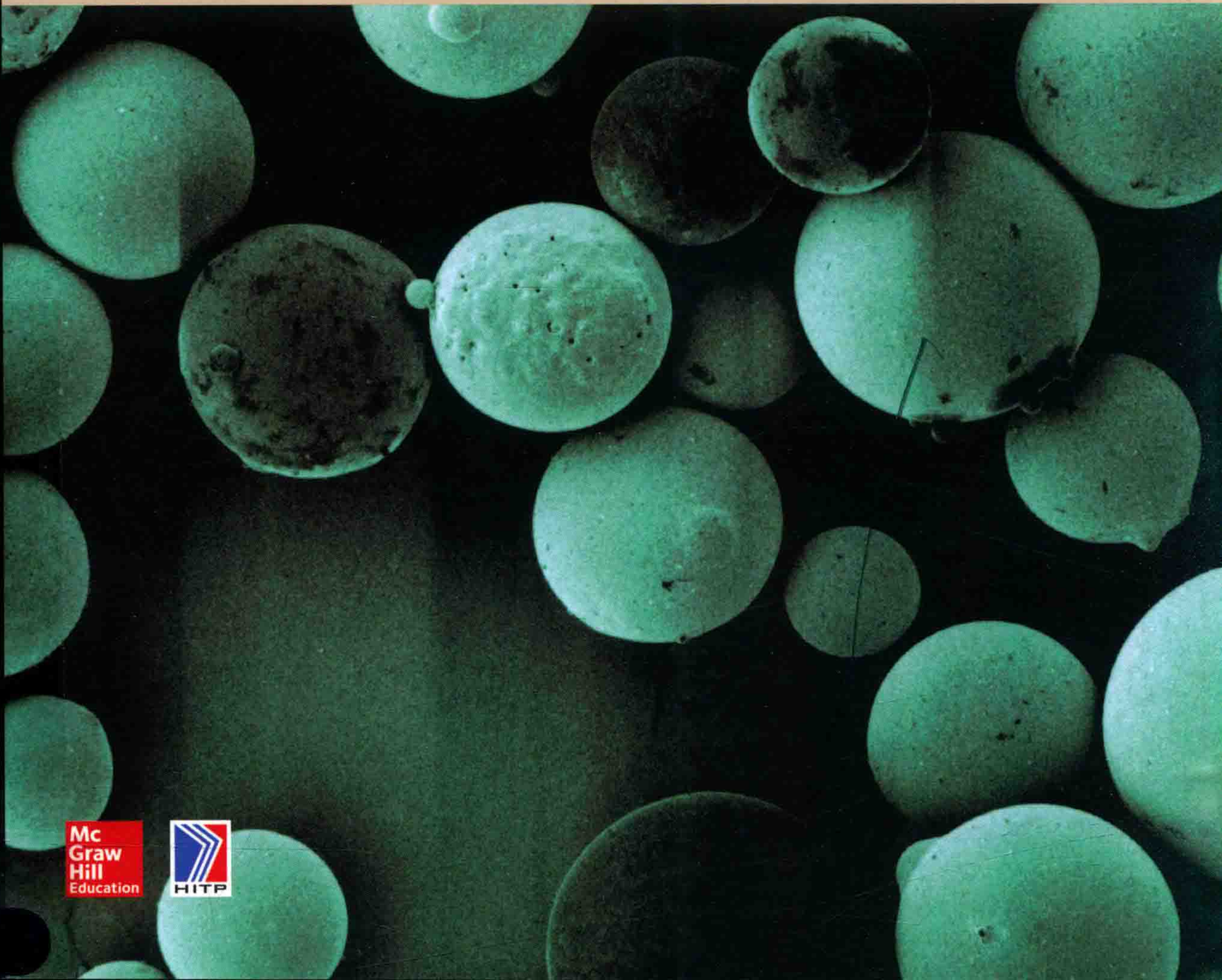
电磁复合材料手册

Electromagnetic Composites Handbook

Models, Measurement, and Characterization

Second Edition

RICK MOORE



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影印版说明

本书是美国 McGraw-Hill Education 公司 2016 年出版的 *Electromagnetic Composites Handbook* Second Edition 的影印版。本书从理论、计算和实验的角度进行材料的表征，涉及非导电介质、半导体材料、导电材料、磁性材料和复合材料等，共提供了 300 多种材料的相关数据。

作者里克•摩尔于 1978 年获得佐治亚理工学院物理学博士学位。多年来专注于电磁测量和光子结构、纤维材料、复合材料的研究，发表相关科技论文 150 余篇。

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ELECTROMAGNETIC COMPOSITES HANDBOOK

Models, Measurement, and Characterization

Rick Moore

McGraw Hill Education

New York Chicago San Francisco Athens London
Madrid Mexico City Milan New Delhi
Singapore Sydney Toronto

PREFACE

Arthur Von Hippel's book, *Dielectric Materials and Application,* was published in 1954. At the time, the development of composites for electrical and electromagnetic technologies was just beginning. Thus, dielectric and magnetic theory, models, measurement techniques, and measured data that were presented by Von Hippel emphasized homogeneous isotropic materials composed of a single molecular species or compound. The vast majority of those materials were electrically insulating and nonmagnetic.

Semiconductor production was in developmental phase, but samples for waveguide measurements (as used by Von Hippel) were not available and the importance of semiconductors for everyday technology was not yet recognized. Shockley's patent on the transistor (#2569347) was just 6 years old. Ferrites were known; however, their application in radio and microwave technology for phase shifters, filters, and isolators were just being realized. They are now applied for suppression of radio frequency interference on computer mother boards, integrated circuits, communication networks, and in electrically small antennas. The use of fiber and laminate-based composites in electromagnetic technologies did not begin until the 1970s.

The *Electromagnetic Composites Handbook* is designed as an engineering and scientific handbook that extends the Von Hippel text to include data on additional nonconducting dielectrics, semiconducting, conducting, and magnetic materials and composites composed of two or more molecularly distinct compounds that are distributed in size scales from nanometers to centimeter dimensions. The development of models that attempt to predict composite constitutive parameters, using constitutive parameters of their constituents, is a parallel effort. The models support predictions of and comparison to measured permittivity and permeability. Permittivity, permeability, impedance, and conductivity data for solids and composites are presented for frequencies from about 1 MHz to 1000 GHz.

Chapters of this book are devoted to the descriptions of electromagnetic constitutive parameter sources, procedures and equipment to measure the parameters, propagation models in composites, prediction of composite properties, and measured constitutive parameter data for the electromagnetic spectrum of wavelengths larger than a few micrometers but mostly in the meter to millimeter wavelengths. Each chapter concludes with a list of references for that chapter. These are indicated in each chapter's text in brackets. MK units are primarily used throughout this book; however, English or CG units may occasionally enter into discussion. The analysis crosses scientific and technological boundaries and thus the scientific complex operator, i, sometimes appears rather than the engineering j for the complex numbers. Note that in the data tables a positive sign, +, is adopted for dielectric and magnetic loss. Modeling and theory chapters discuss various composite models and then apply the most successful analytical and numerical methodologies to typical electromagnetic design problems that often use electromagnetic composites in their solution, again for wavelengths larger than a few micrometers.

Reflection and transmission line measurements, such as those of Von Hippel, are the framework from which composite material measurements began and those measurement techniques are reviewed. The review is followed by a discussion of advances in the measurement technology since 1980. For example, the microwave and millimeter wave application of lens-based open cavities and free space measurements, common for infrared and optical spectra, is one advance. The techniques include Fabry–Perot and etalon derivatives. The adoption of the infrared and optical techniques for millimeter, centimeter, and even meter wavelengths and the use of various multi-mode resonant cavity configurations, was facilitated by the second major technology addition, i.e., the development of the automatic network analyzer (ANA) and digital receivers–transmitters that had modest power (hundreds of milliwatts), broad bandwidth frequency, synthesized sources, and matched adapters. A third advance was microwave and millimeter antennas with bandwidths larger than 20:1. Advances in electromagnetic tools, instrumentation, and "borrowing" of lens-based measurements now allow accurate measurement of isotropic or anisotropic constitutive properties for single samples from a few hundred megahertz to above 100 GHz.

Some composites may contain constituents that are distributed in size scales of nanometer to centimeter dimensions. The larger scales make the composite electrically inhomogeneous at higher frequencies since inhomogeneity is determined by the ratio of the physical size of the composite phases and the electromagnetic wavelength. Characterizing the large-scale composites by effective permittivity and/or permeability is not sufficient. In cases where physical scales of the composite components are small but their electrical scale approach unity, diffuse and/or bistatic electromagnetic scatter modeling and measurements may be used to expand understanding of electromagnetic observables (reflection, transmission, and absorption) and calculated, effective magnetic permeability and electrical permittivity of composites. Measurement techniques that apply to some electrically inhomogeneous composites can also be used for isotropic, homogeneous materials. Numerical models will be discussed that give insight into electromagnetic properties of inhomogeneous electromagnetic composites and the problems that may be encountered in their utilization.

The advances discussed in this handbook are significant to both electromagnetic engineers and theoreticians. ANA advances now allow continuous measurement and thus material parameter data over 1000:1 or greater bandwidths. With such a dense database, experimentalists and engineers can confidently design broadband meter, microwave, and millimeter wave devices and material constructs. A physicist, chemist, or material scientist benefits from the high data density in verification of electromagnetic composite material theories over bandwidths that encompass multiple physical and electrical scales, material dimensionalities, and material physics. Examples are multiphase magnetics, periodic dielectrics exhibiting photonic bandgaps, and material constructs with negative index behavior.

The book concludes by presenting dielectric and magnetic parametric fits to measured data for almost 300 composites and/or composite components. Many gigabytes of data contributed to the preparation of this book and a comprehensive presentation of complex permittivity and permeability in tabular form were not possible due to space limitations; however, a digital database is planned for the future. For now, the parametric fits of Chap. 12 supply frequency and temperature dispersive data that are presented as analytic equations whose forms are based upon solid-state physics. The frequency and/or temperature range used for each fit are annotated with the equation parameters. Measurements range from 1 MHz to a few hundred gigahertz. Data density was typically at 1 MHz intervals below 100 MHz, 10 MHz spacing from 100 MHz to 1 GHz, and 100 MHz spacing above 1 GHz. The complex magnetic permeability and permittivity are fit to a range of relaxation models. Measurement frequencies are above characteristic solid-state Debye relaxation frequencies and below terahertz to infrared molecular relaxations. Power laws in frequency coupled with a single resonant model produce excellent parameterizations for permittivity data, especially those of composites containing semiconducting components. Overall, the parametric fits aid in spanning measurement frequency gaps and in interpretation of material physics.

Selected composite data are presented for measurements made before and during exposure to environmental extremes of temperature. For example, ceramic and ceramic composites are often used in high-temperature environments; thus data are shown from ambient to temperatures in excess of 2200 K. Exponential functions (typical of semiconductors) are used for temperature dependence of ceramics and ceramic fibers.

Select materials were chosen to overlap data of Von Hippel and other publications for comparison. Some data are repeated for identical material compositions, but from different suppliers, and thus illustrate unsurprising variability. Data on composites may be for "identical" compositions but are included to illustrate variability in manufacturing and source.

ACKNOWLEDGMENTS

This book has grown over the past 35 years and matured to its final form in the last 5 years. Many colleagues at the Georgia Tech Research Institute (GTRI) contributed to the development of the many GTRI measurement systems that are described or pictured in this text. An attempt to list those who gave special contributions is below. The list is in rough historical order:

Drs. Patrick Montgomery and Thomas B. Wells for transmission line analyses, inversion algorithms, and design of Fabry-Perot systems;

Mr. Thomas Taylor, Paul Friedrich, and Mrs. Anita Pavadore for design, assembly, and making work, high temperature cavities, transmission lines, and focused beam systems;

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Finally, I must remember Mr. James Gallagher, the Georgia University System's first Regents' Researcher. Jim redirected me down a path of measurement in 1981.

CONTENTS

INTRODUCTION

Over the last 50 years and since the Von Hippel's text [1], multifunctional and frequency dispersive electromagnetic composites have become intertwined in aerospace, computer, sensor, communication, and structural engineering. Aerospace applications are exemplified in the Space Shuttles, Northrop B2, and Boeing 787 aircraft [2–4]. Space shuttle tiles are multifunctional examples that meet structure, impact, temperature stability, and thermal conductivity specifications. However, the same tiles also covered and protected communication and radar antennas and thereby operated as environmentally resistant, temperature stable, radio frequency radomes. Composite laminates are routinely found as circuit substrates. Energy-efficient windows for skyscrapers must be optically transparent and are often infrared reflective. However, if cell phone and wireless access are required, the same window must have transparency from hundreds of megahertz to tens of gigahertz. Alternatively, window specifications may call for radio frequency isolation to limit wireless access within the structure. In either case, the window can incorporate semiconducting film and components to achieve the required frequency dispersions. Magnetic micrometer and nanometer particulates are found in electromagnetic interference materials and are applied as MRI enhancers and for the treatment for cancer. Composites are also used to construct lenses, waveguide, photonic bandgap, and/or structures that produce an effective negative index of the structure. These examples often incorporate semiconducting, artificial dielectric, conducting, and magnetic components.

The electromagnetic models, measurement techniques, and measured data of this book are chosen to aid development of multifunctional material designs. Models and measurement apply to composites made with components of sizes from tens of nanometers to centimeters. Goals of this text are to contribute to current and visionary electromagnetic composite applications and supply an extension of the Von Hippel database for composites.

OUTLINE

Chapter 1 introduces the following chapters and establishes definitions, terminology, Maxwell's equations, electromagnetic propagation, and concepts of electromagnetic material constitutive parameters. Physics and physical sources of electromagnetic permittivity, permeability, and conductivity are discussed in Chaps. 2 and 3, respectively, for the electromagnetic spectrum between approximately 1 MHz and a few terahertz. Concepts that are discussed include the field polarization, interfacial contact between composite constituents, electron spin, magnetic domains, sizes and shapes, periodicities of composition, and free charge carrier density. All play parts in determining frequency dispersive constitutive parameters in the above electromagnetic frequency range and therefore limit the solid-state functional forms that are used in parametrically fitting measured data of Chap. 12.

Controlled constitutive parameter temperature dependence can be a significant advantage in composites and therefore various sources and methods for reduction of temperature variation are also discussed in Chaps. 2 and 3. Kramer–Kronig (K–K) relations are introduced in Chap. 3 as a physics-based analysis to evaluate measurement accuracy and causality of measured data. K–K analyses are made easier by the advances in measurement technology arising from wideband, phase-locked electromagnetic sources and digital amplitude and phase analyzers and receivers. However, K–K still has strongest application for characterization at the infrared and optical spectral region. In those wave bands power reflection and transmission amplitude are easily measured over many decades of frequency but continuous frequency *phase* measurements are not easily obtained. With the advent of network analyzer systems, digital receivers/sources, and free space characterization techniques, 100:1 and even 1000:1 bandwidths of data can be obtained on single material samples in the meter through millimeter wavelength regime. The multi-decade bandwidths support K–K analysis at lower wave bands.

Chapter 4 is devoted to descriptions of propagation models that are used to calculate electromagnetic observables (plane wave reflection and transmission coefficients) from constitutive data and also used for the inverse function, i.e., calculating constitutive parameters from measured reflection and transmission. The measurement techniques described in this book acquire measured plane wave reflection and transmission voltage amplitude and phase as their observables. Analyses of Chapter 4 relate that reflection and transmission to frequency dispersive isotropic and/or anisotropic permittivity, permeability, and conductivity of material layers that are contained within laminar structures. Layers may have arbitrary thickness and may themselves be composites or mixtures. Electromagnetic boundary value problems are initially used to develop propagation and reflection equations under the assumption that the materials have electromagnetic components with characteristic electromagnetic scale, much smaller than the interrogating electromagnetic wavelength. Impacts of large-scale discrete components are addressed in later chapters under discussions of numerical modeling.

Chapter 4 also presents propagation models in the context of scattering-cascade matrices [5] and shows how to apply these to multilayer structures so long as internal material laminates are electrically homogeneous. Both isotropic and anisotropic propagation models are presented. Example calculations of reflection and transmission coefficients are shown for planar electromagnetic waves, for waves incident from various angles, and for different laminate constructions. The analysis is also described that demonstrates that reflection and transmission measurements, at various angles and sample orientations, can be combined with the geometric construction of the laminate to apply scattering matrices and infer the effective constitutive parameters of a laminate or laminate layers. The chapter includes the discussion of the impact of small variations in constitutive parameters on reflection and transmission. The chapter concludes by presenting discussions, models, and calculated examples of propagation in diagonal and fully anisotropic materials. Calculations are presented to establish a baseline with which other models and future measurements can be compared. Examples of composite applications and use of scattering matrices are found throughout the book.

Chapters 5 to 7 address effective media theory (EMT) methodologies to predict composite properties from those of their constituents. Models presented in these chapters can assist the experimenter in analyses that bound expectations for measured electromagnetic properties. Models also place limits on electromagnetic size scale for material components that are used in composites and yet allow the composite to be characterized by using measured effective homogeneous anisotropic permittivity and permeability that are used in scattering matrix analysis. The chapters are ordered in hierarchical EMT complexity, electrical scale of the composites, parameters to be modeled, and composite chemistry/composition. The coherent potential approximation is used to derive and apply various electromagnetic scattering-based EMT. This application of the coherent potential approximation has been used by many authors but here it will be discussed in the context of two books: *Wave Propagation and Scattering in Random Media* by Akira Ishimaru [6] and *Introduction to Wave Scattering, Localization and Mesoscopic Phenomena* by Ping Sheng [7].

Chapter 5 supplies an introduction to effective media concepts and derives common forms of EMTs by application of the coherent potential approximation. General limits are established on dielectric composite composition, component size, and constitutive parameter so that simple EMT can be applied. The emphasis is placed on spherical inclusions since they can easily supply physical insight into particulate coating effects, higher order scattering, and constitutive parameter complexity. The EMTs are applied to simple dielectric composites composed of a matrix and single electrically small particulate which is at a low fractional volume. Particulate shape and aspect ratio are incorporated to illustrate anisotropies that may be encountered in arrayed or physically thin composites.

Chapter 6 begins with extension of effective media equations to semiconducting and conducting particulates and high volume fraction compositions. The addition of semiconductor or conducting particulates facilitates the synthesis of artificial dielectrics; however, effective media models must be extended to include electrical percolation within the composite. Correct description of the percolation requires details on particulate and composite geometry. The importance of multiscale modeling (nanometer to centimeter) is illustrated in Chap. 11 by considering micrometer size dielectric spheres that are coated with nanoscale conducting films.

Percolation introduces constitutive parameter dependence on composite geometry and dimensionality. In general the permittivities of these composites show a power law frequency dispersion, and have anisotropy in thin layers and their constitutive parameters scale with composite sample size. Additional physical observables may include anomalous power loss that actually arises from diffuse scatter; local electric field strength concentration and "plasmon" resonance. Examples of phenomenon will be discussed to establish foundations for measurement system requirements and equipment for characterizing these composite types.

Chapter 6 further extends analysis of artificial dielectrics to the study of artificial-dielectric-magnetic materials. Though most EMTS appear to be easily mapped to permeability, they are accurate only when low-volume fractions of multi-domain magnetic particulates are dispersed in the composite. Examples are given of EMT applied for dense composites containing magnetic components. Fundamentally, EMTs fail to account for magnetic coupling between magnetic particles within a composite. Accurate models that account for complex magnetic particulate coupling and combinations with artificial dielectrics would appear to require numerical approaches rather than simple computations using effective media equations.

Numerical methods in composite analysis are topics for Chap. 7. The method of moment (MoM) and finite-difference time domain (FDTD) numerical techniques are reviewed. Properties of artificial dielectrics near the percolation threshold and artificial dielectrics in magnetic media are also discussed. Interactive models of magnetic and conducting components can support negative index material concepts [8–10], photonic bandgap materials [11], and other metamaterials [11–13] which are active areas of research in materials engineering. Examples are given of numerical model applications to predict the electromagnetic observables in dense composites and those that have large electrical scales. The implications of the model's predictions are that electromagnetic characterization of many artificial and/or metamaterials may require equipment beyond those applied to measure simple isotropic dielectrics or magnetics.

Chapter 8 begins discussion of measurement techniques and equipment configurations and provides a summary of a 30-year evolution of equipment and measurement procedures for electromagnetic material characterization. The ability to perform accurate 10:1, 100:1, and even 1000:1 bandwidth electromagnetic measurements was significantly advanced by development of various network analyzers by Hewlett-Packard (now Agilent) and Wiltron; automated multi-port receiver and transmitter systems (e.g., Scientific Atlanta, now MI Technologies of Norcross Georgia), and rapidly scanned frequency-synthesized sources (e.g., Agilent and Wiltron). The computer-controlled network analyzer's compact combination of ultra low noise receiver and frequency-power stable source allowed the electrical engineer and/or material scientist to rapidly adapt waveguides or other transmission line, resonant cavity, or antenna systems to make characterizations of the isotropic or anisotropic materials.

Chapter 8 discussions focus on the measurement techniques using transmission line and plane wave scattering analysis. Discussions include system designs and configurations, discussion of error correction procedures, sample preparation, problems encountered with high-dielectric or high-permeability materials and inversion algorithms that calculate electromagnetic constitutive parameters from the measurement. Descriptions of reflection and transmission measurements (waveguide, coaxial line, and free space) are presented that allow characterization of homogeneous but inherently anisotropic materials (i.e., at the molecular lattice scale) such as magnetic ferrites. Focused beam free space systems are summarized. The focused beam systems were historically used in gas spectroscopy, plasma, and charged particle beam characterization.

Chapter 9 continues the measurement system design but emphasizes resonant measurement techniques and repeats many of the same system studies. Error corrections, perturbative and exact cavity measurements, transmission line, and cavity combinations are discussed in the context of network analyzer utilization.

Chapter 10 extends discussions of transmission line, free space, and cavity techniques and applies them for material measurements in low- and high-temperature environments and for anisotropic magnetic materials. Commercial environmental systems are discussed that allow characterization over modest temperature ranges (e.g., 170 to 500 K) and lower frequencies (<1 GHz); however, the customization of the measurement system for specific and higher temperature ranges is often required.

Chapter 11 continues measurement discussions with emphasis on impacts of very small size scales and illustrates how RF material characterization techniques can be applied in the field of nano material composite engineering. Three test cases are presented to illustrate micro and nano composite impacts. The cases address ferrites, nano magnetite and nano–micro metal composites. Nano and micro sizes require additions to macroscopic characterization. It is often difficult to isolate nano particulates for the measurement, e.g., nano grains of iron or carbon may spontaneously combust in air. However, these and other developmental nano material particulates precipitate from solution or can be deposited and/or trapped within polymer or ceramic matrices and substrates. The electromagnetic sensing of these materials pose a small volume problem for the measurement; however, if measurements are combined with selected effective medium theories, RF characterization can supply fundamental properties of the nano particulates that are contained within the composite. Detection and characterization of nano metallic particulates leverage optical absorption and characteristic color change. However, many magnetic nanoparticles are nonconductors or have greatly reduced conductivity. The detection or characterization of the nanoparticles in small volumes requires the experimenter to return to resonant cavity measurements. Two example measurements are described.

Chapter 12 concludes the text and contains the derived parametric fits to data of approximately 300 commercial composite and laboratory-developed test materials. Data were acquired using many techniques including circular and rectangular waveguide cavities, waveguide, coaxial line, free space focused beam systems, stripline and Fabry–Perot resonators. Selected material measurements are made at identical frequencies but using different techniques. In other cases, measurements of multiple samples of the same material are shown to illustrate expectations in material reproducibility, a problem with many particulate composites.

The material types and data tables of Chap. 12 are grouped as follows: (1) polymers (those used in composites), (2) polymer-fiber composites, (3) nonmagnetic solid ceramics, (4) dielectric fibers, (5) ferrites, (6) semiconductors and films, (7) semiconductor–polymer composites, (8) foams and honeycombs, (9) ferrite–polymer composites, (10) iron–polymer composites, and (11) three-phase (Fe-ferrite-polymer) composites.

Measured frequency ranges vary for each material. Data on ferrites and magnetic composites may extend from 1 MHz to 18 GHz. This range encompasses frequencies where magnetic dispersions for these ferrites are most apparent. Chapter 11 includes microscopic discussions for selected ferrites in the Chap. 12 database. Measurements of polymers and fiber–polymer dielectric composites, foams, and honeycombs emphasize millimeter wavelengths. Below about 20 GHz (about 1.5-cm wavelength) these composites are electrically homogeneous and thus the lowest frequency measurement (e.g., X band) can logically be extended for lower frequency design problems. If the material is a semiconductor, a frequency scale of f^{-a} may be required for the imaginary part of the permittivity. At millimeter wavelengths inhomogeneity in composites is manifest. Diffuse scatter may contribute to some anomalous frequency dispersions in the permittivity.

Complex permittivity for ceramics and ceramic fibers are presented as functions of frequency and temperature. Ceramics and ceramic fibers are often used at elevated temperatures. Their temperature sensitivity can be important for application in ceramic filters and resonators. Since the ceramic grain sizes are a few micrometers or less, and the materials bind any free electrons in oxides, nitrides, or borides, they have very large resistances. Thus, frequency dispersion at ambient temperature is often not observed. For this reason, solid ceramics such as fused quartz are considered to be dielectric "standards." Measured data on these high-density small grain materials sometimes do cover a large bandwidth. For example, the fiber ceramic's measurement frequencies are in the 2 to 18 GHz band. In select cases data from a few gigahertz to 100 GHz are shown for some ceramic foams and layered ceramics since they demonstrate some dispersion at frequencies above 40 GHz. However, this dispersion is attributed to scattering of ceramic composite component sizes.

For fibers and ceramics, permittivity–temperature data were acquired by measuring at one or at most a few frequencies in the 2 to 100 GHz band. During the measurement samples were often immersed in the temperature environment for long periods. Solid ceramics were maintained within an oven or environmental chamber while the temperature was raised or lowered to a goal value and thus they were temperature-saturated between measurements. Solid ceramics were exposed to temperatures as high as 2200 K or until the temperature resulted in structural changes. Measurements at the highest temperatures were performed in near vacuum and some samples lost 50 percent of their mass in vaporization. Fibers were measured in a closed, inert gas-filled resonance cavity and removed from the cavity between temperatures. Their exposure at each temperature (ambient to 1500 K) was 1 to 5 min.

The complex permittivity, impedance, transmission, and reflection coefficients are presented for selected commercial semiconductors, semiconducting films, and semiconducting composites. Measurement frequencies for semiconducting films are in the 200 MHz to 18 GHz range. These measurements are important since they illustrate the differences that are observed in DC four-point probe resistance data (most often quoted by manufacturers) and AC resistance that is derived from voltage transmission coefficients.

Measurements of solid semiconductors are most often for 2 to 12 GHz with selected semiconductors including data measured above 100 GHz. Data for semiconducting composites were acquired from about 200 MHz through 100 GHz. The wide frequency range was chosen to demonstrate frequency dispersions that are exhibited by electrically percolating systems. These data are particularly applicable for testing predictions of effective medium theories.

Other groups of composite materials use two components. They are Fe or ferrite polymer blends. There is also a select group of three-phase composites which use the ferrite, Fe, and polymer. Composites are made with controlled volume fractions of magnetic particulates. Measurements of different samples, made with "identical" volume fractions, are sometimes supplied to illustrate the statistical variation that is inherent in composites. Additional data are also presented for commercial Fe–polymer composites; Fe–polymer composites that use differing size magnetic particulate and commercial Fe–Si particulates. Data from approximately 10 MHz to 18 GHz were acquired and used to determine parameters of the Lorentzian fit to permeability. The complex permittivity in Fe composites displayed significant dielectric dispersion at the highest volume fractions. The dispersion is attributed to a finite DC conductivity in the composite, presumably due to contacting Fe particulates. It is noted that commercial Fe composites had permittivity and permeability very near to those prepared in the laboratory so long as their specific gravity was close. The ferromagnetic data sets are comprehensive in frequency and it is hoped that analysis of the data by other researchers may lead to usable analytical effective medium equations that contain more complete material physics. Please note that the following disclaimer applies for all measured data of Chap. 12.

A disclaimer for all parametric fits and plotted data applies. All data and parametric fits represent measured results using a range of experimental facilities and techniques. The data were obtained by the author and colleagues using samples prepared in the laboratory or commercial materials, either purchased or supplied gratis. Data often are from a few samples. Composite constructions are inherently statistical and thus variations in properties may be observed. Therefore, data are not "guaranteed" by a manufacturer or the author. Users of the products or laboratory compositions should verify properties before their use. The material properties and data fits are to be guides for engineering design or as input to material models or analysis.

Finally, in preparation of the book a broad survey of published commercial and manufacturing electromagnetic and physical data on materials was performed. When available, these data and references to the source are included with tabulation of measured data parameters.

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