PART I

FUNDAMENTALS

CHAPTER 1

INTRODUCTION

Many advances in electromagnetic theory were made in recent years in response to new applications of the theory to microwaves, millimeter waves, optics, and acoustics; as a result, there is a need to present a cohesive account of these advances with sufficient background material. In this book we present the fundamentals and the basic formulations of electromagnetic theory as well as advanced analytical theory and mathematical techniques and current new topics and applications.

In Chapter 2, we review the fundamentals, starting with Maxwell's equations and covering such fundamental concepts and relationships as energy relations, potentials, Hertz vectors, and uniqueness and reciprocity theorems. The chapter concludes with linear acoustic-wave formulation. Plane-wave incidence on dielectric layers and wave propagation along layered media are often encountered in practice. Examples are microwaves in dielectric coatings, integrated optics, waves in the atmosphere, and acoustic waves in the ocean. Chapter 3 deals with these problems, starting with reviews of plane waves incident on layered media, Fresnel formulas, Brewster's angle, and total reflection. The concepts of complex waves, trapped surface waves, and leaky waves are presented with examples of surface-wave propagation along dielectric slabs, and this is followed by discussion on the relation between Zenneck waves and plasmons. The chapter concludes with Wentzel–Kramers–Brillouim (WKB) solutions and the Bremmer series for inhomogeneous media and turning points, and WKB solutions for the propagation constant of guided waves in inhomogeneous media such as graded-index fibers.

Electromagnetic Wave Propagation, Radiation, and Scattering: From Fundamentals to Applications,
Second Edition. Akira Ishimaru.

Chapter 4 deals with microwave waveguides, dielectric waveguides, and cavities. Formulations for transverse magetic (TM), transverse electric (TE), and transverse electromagnetic (TEM) waves, eigenfunctions, eigenvalues, and the k–β diagram are given, followed by pulse propagation in dispersive media. Dielectric waveguides, step-index fibers, and graded-index fibers are discussed next with due attention to dispersion. It concludes with radial and azimuthal waveguides, rectangular and cylindrical cavities, and spherical waveguides and cavities. This chapter introduces Green's identities, Green's theorem, special functions, Bessel and Legendre functions, eigenfunctions and eigenvalues, and orthogonality.

One of the most important and useful tools in electromagnetic theory is Green's functions. They are used extensively in the formulation of integral equations and radiation from various sources. Methods of constructing Green's functions are discussed in Chapter 5. First, the excitation of waves by electric and magnetic dipoles is reviewed. Three methods of expressing Green's functions are discussed. The first is the representation of Green's functions in a series of eigenfunctions. The second is to express them using the solutions of homogeneous equations. Here, we discuss the important properties of Wronskians. The third is the Fourier transform representation of Green's functions. In actual problems, these three methods are often combined to obtain the most convenient representations. Examples are shown for Green's functions in rectangular waveguides and cylindrical and spherical structures.

Chapter 6 deals with the radiation field from apertures. We start with Green's theorem applied to the field produced by the sources and the fields on a surface. Here, we discuss the extinction theorem and Huygens' formula. Next, we consider the Kirchhoff approximation and Fresnel and Fraunhofer diffraction formulas. Spectral representations of the field are used to obtain Gaussian beam waves and the radiation from finite apertures. The interesting phenomenon of the Goos–Hanchen shift of a beam wave at an interface and higher-order beam waves are also discussed. The chapter concludes with the electromagnetic vector Green's theorem, Stratton–Chu formula, Franz formula, equivalence theorem, and electromagnetic Kirchhoff approximations.

The periodic structures discussed in Chapter 7 are used in many applications, such as optical gratings, phased arrays, and frequency-selective surfaces. We start with the Floquet-mode representation of waves in periodic structures. Guided waves along periodic structures and plane-wave incidence on periodic structures are discussed using integral equations and Green's function. An interesting question regarding the Rayleigh hypothesis for scattering from sinusoidal surfaces is discussed. Also included are the coupled-mode theory and co-directional and contra-directional couplers.

Chapter 8 deals with material characteristics. We start with the dispersive characteristics of dielectric material, the Sellmeier equation, plasma, and conductors. It also includes the Maxwell–Garnett and Polder–van Santen mixing formulas for the effective dielectric constant of mixtures. Wave propagation characteristics in magnetoplasma, which represents the ionosphere and ionized gas, and in ferrite, used in microwave networks, are discussed as well as Faraday rotation, group velocity, warm plasma, and reciprocity relations. This is followed by wave propagation in chiral material. The chapter concludes with London's equations and the two-fluid model of superconductors at high frequencies.

Chapter 9 presents selected topics on antennas, apertures, and arrays. Included in this chapter are radiation from current distributions, dipoles, slots, and loops. Also discussed are arrays with nonuniform spacings, microstrip antennas, mutual couplings, and the integral equation for current distributions on wire antennas. Chapter 10 starts with a general description of the scattering and absorption characteristics of waves by dielectric and conducting objects. Definitions of cross sections and scattering amplitudes are given, and Rayleigh scattering and Rayleigh–Debye approximations are discussed. Also included are the Stokes vector, the Mueller matrix, and the Poincaré sphere for a description of the complete and partial polarization states. Techniques discussed for obtaining the cross sections of conducting objects include the physical optics approximation and the moment method. Formal solutions for cylindrical structures, spheres, and wedges are presented in Chapter 11, including a discussion of branch points, the saddle-point technique, the Watson transform, the residue series, and Mie theory. Also discussed is diffraction by wedges, which will be used in Chapter 13.

Electromagnetic scattering by complex objects is the topic of Chapter 12. We present scalar and vector formulations of integral equations. Babinet's principle for scalar and electromagnetic fields, electric field integral equation (EFIE), and magnetic field integral equation (MFIE) are discussed. The T-matrix method, also called the extended boundary condition method, is discussed and applied to the problem of sinusoidal surfaces. In addition to the surface integral equation, also included are the volume integral equation for two- and three-dimensional dielectric bodies and Green's dyadic. Discussions of small apertures and slits are also included.

Geometric theory of diffraction (GTD) is one of the powerful techniques for dealing with high-frequency diffraction problems. GTD and UTD (uniform geometric theory of diffraction) are discussed in Chapter 13. Applications of GTD to diffraction by slits, knife edges, and wedges are presented, including slope diffraction, curved wedges, and vertex and surface diffractions.

Chapter 14 deals with excitation and scattering by sources, patches, and apertures embedded in planar structures. Excitation of a dielectric slab is discussed, followed by the WKB solution for the excitation of waves in inhomogeneous layers. An example of the latter is acoustic-wave excitation by a point source in the ocean. Next, we give general spectral formulations for waves in patches, strip lines, and apertures embedded in dielectric layers. Convenient equivalent network representations are presented that are applicable to strip lines and periodic patches and apertures.

The Sommerfeld dipole problem is that of finding the field when a dipole is located above the conducting earth. This classical problem, which dates back to 1907, when Zenneck investigated what is now known as the Zenneck wave, is discussed in Chapter 15, including a detailed study of the Sommerfeld pole, the modified saddle-point technique, lateral waves, layered media, and mode representations.

The inverse scattering problem in Chapter 16 is one of the important topics in recent years. It deals with the problem of obtaining the properties of an object by using the observed scattering data. First, we present the Radon transform, used in computed

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tomography or X-ray tomography. The inverse Radon transform is obtained by using the projection slice theorem and the back projection of the filtered projection. Also included is an alternative inverse Radon transform in terms of the Hilbert transform. For ultrasound and electromagnetic imaging problems, it is necessary to include the diffraction effect. This leads to diffraction tomography, which makes use of back propagation rather than back projection. Also discussed are physical optics inverse scattering and the holographic inverse problem. Abel's integral equations are frequently used in inverse problems. Here, we illustrate this technique by using it to find the electron density profile in the ionosphere. Polarimetric radars are becoming increasingly more important because of the advances in polarimetric measurement techniques. We present the fundamentals of polarimetry and optimization as well as polarization signatures.

Chapter 17 presents fundamentals of radiometry and noise. The definitions of antenna temperature, radiative transfer theory, and the scattering cross section of surfaces are given, followed by consideration of system noise temperature and minimum detectable temperature. Also included is a discussion on the determination of sky brightness distribution by interferometry used in radio astronomy. Here, we discuss the Fourier transform and convolution relationships among the aperture distribution, the radiation pattern, and sky brightness distributions.

Chapters 18 through 26 were added for the second edition of this book. The contents of those chapters are summarized in the Preface to the Second Edition.

The appendices give many formulas and detailed derivations of equations that are too lengthy to be included in the text. They should be helpful in understanding the material in the text.

Useful reference books on electromagnetics at the intermediate undergraduate level include Ramo et al. (1965), Jordan and Balmain (1968), Wait (1986), Shen and Kong (1987), and Cheng (1983). Among books at the advanced level are Stratton (1941), Harrington (1961), Collin (1966), Felsen and Marcuvitz (1973), Schelkunoff (1965), Balanis (1989), Kong (1981, 1986), Jones (1964, 1979), and Van Bladel (1964).