Electromagnetic
Waves and Antennas

Electromagnetic Waves and Antennas

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To Monica and John

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Preface

This text provides a broad and applications-oriented introduction to electromagnetic waves and antennas. Current interest in these areas is driven by the growth in wireless and fiber-optic communications, information technology, and materials science.

Communications, antenna, radar, and microwave engineers must deal with the generation, transmission, and reception of electromagnetic waves. Device engineers working on ever-smaller integrated circuits and at ever higher frequencies must take into account wave propagation effects at the chip and circuit-board levels. Communication and computer network engineers routinely use waveguiding systems, such as transmission lines and optical fibers. Novel recent developments in materials, such as photonic bandgap structures, omnidirectional dielectric mirrors, birefringent multilayer films, surface plasmons, negative-index metamaterials, slow and fast light, promise a revolution in the control and manipulation of light and other applications. These are just some examples of topics discussed in this book. The text is organized around three main topic areas:

- The propagation, reflection, and transmission of plane waves, and the analysis and design of multilayer films.
- Waveguides, transmission lines, impedance matching, and *S*-parameters.
- Linear and aperture antennas, scalar and vector diffraction theory, antenna array design, numerical methods in antennas, and coupled antennas.

The text emphasizes connections to other subjects. For example, the mathematical techniques for analyzing wave propagation in multilayer structures and the design of multilayer optical filters are the same as those used in digital signal processing, such as the lattice structures of linear prediction, the analysis and synthesis of speech, and geophysical signal processing. Similarly, antenna array design is related to the problem of spectral analysis of sinusoids and to digital filter design, and Butler beams are equivalent to the FFT.

Use

The book is appropriate for first-year graduate or senior undergraduate students. There is enough material in the book for a two-semester course sequence. The book can also be used by practicing engineers and scientists who want a quick review that covers most of the basic concepts and includes many application examples.

The book is based on lecture notes for a first-year graduate course on "Electromagnetic Waves and Radiation" that I have been teaching at Rutgers for more than twenty years. The course draws students from a variety of fields, such as solid-state devices, wireless communications, fiber optics, biomedical engineering, and digital signal and array processing. Undergraduate seniors have also attended the graduate course successfully.

The book requires a prerequisite course on electromagnetics, typically offered at the junior year. Such introductory course is usually followed by a senior-level elective course on electromagnetic waves, which covers propagation, reflection, and transmission of waves, waveguides, transmission lines, and perhaps some antennas. This book may be used in such elective courses with the appropriate selection of chapters.

At the graduate level, there is usually an introductory course that covers waves, guides, lines, and antennas, and this is followed by more specialized courses on antenna design, microwave systems and devices, optical fibers, and numerical techniques in electromagnetics. No single book can possibly cover all of the advanced courses. This book may be used as a text in the initial course, and as a supplementary text in the specialized courses.

Contents and Highlights

The first eight chapters develop waves concepts and applications. The material progresses from Maxwell equations, to uniform plane waves in various media, such as lossless and lossy dielectrics and conductors, birefringent and chiral media, including negative-index media, to reflection and transmission problems at normal and oblique incidence, including reflection from moving boundaries and the Doppler effect, to multilayer structures.

Chapter three deals with pulse propagation in dispersive media, with discussions of group and front velocity and causality, group velocity dispersion, spreading and chirping, dispersion compensation, slow, fast, and negative group velocity, and an introduction to chirp radar and pulse compression.

Some of the oblique incidence applications include inhomogeneous waves, total internal reflection, surface plasmons, ray tracing and atmospheric refraction, and Snel's law in negative-index media.

The material on multilayer structures includes the design of antireflection coatings, omnidirectional dielectric mirrors, broadband reflectionless multilayers, frustrated total internal reflection and surface plasmon resonance, perfect lenses in negative-index media, polarizing beam splitters, and birefringent multilayer structures.

Chapters 9–13 deal with waveguides and transmission lines. We cover only rectangular waveguides, resonant cavities, and simple dielectric waveguides. The transmission line material includes a discussion of microstrip and coaxial lines, terminated lines, standing wave ratio and the Smith chart, and examples of time-domain transient response of lines. We have included some material on coupled lines and crosstalk, as well as some on coupled mode theory and fiber Bragg gratings.

We devote one chapter to impedance matching methods, including multisection Chebyshev quarter-wavelength transformers, quarter-wavelength transformers with se-

ries or shunt stubs, single stub tuners, as well as L-section and Π-section reactive matching networks.

Chapter 13 presents an introduction to S-parameters with a discussion of input and output reflection coefficients, two-port stability conditions, transducer, operating, and available power gains, power waves, simultaneous conjugate matching, noise figure circles, illustrating the concepts with a number of low-noise high-gain microwave amplifier designs including the design of their input and output matching circuits.

Chapters 14–22 deal with radiation and antenna concepts. We begin by deriving expressions for the radiation fields from current sources, including magnetic currents, and then apply them to linear and aperture antennas. Chapter 15 covers general fundamental antenna concepts, such as radiation intensity, power density, directivity and gain, beamwidth, effective area, effective length, Friis formula, antenna noise temperature, power budgets in satellite links, and the radar equation.

We have included a number of linear antenna examples, such as Hertzian and half-wave dipoles, traveling, vee, and rhombic antennas, as well as loop antennas.

Two chapters are devoted to radiation from apertures. The first discusses Schelkunoff's field equivalence principle, magnetic currents and duality, radiation fields from apertures, vector diffraction theory, including the Kottler, Stratton-Chu, and Franz formulations, extinction theorem, Fresnel diffraction, Fresnel, zones, Sommerfeld's solution to the knife-edge diffraction problem, geometrical theory of diffraction, Rayleigh-Sommerfeld diffraction theory and its connection to the plane-wave spectrum representation with applications to Fourier optics.

The second presents a number of aperture antenna examples, such as open-ended waveguides, horn antennas, including optimum horn design, microstrip antennas, parabolic and dual reflectors, and lens antennas.

Two other chapters discuss antenna arrays. The first introduces basic concepts such as the multiplicative array pattern, visible region, grating lobes, directivity including its optimization, array steering, and beamwidth.

The other discusses several array design methods, such as by zero placement, Fourier series method with windowing, sector beam design, Woodward-Lawson method, and several narrow-beam low-sidelobe designs, such as binomial, Dolph-Chebyshev, Taylor's one-parameter, Taylor's $\bar{n}$ distribution, prolate, and Villeneuve array design. We have expanded on the analogies with time-domain DSP concepts and filter design methods. We finally give some examples of multibeam designs, such as Butler beams.

The last two chapters deal with numerical methods for linear antennas. Chapter 21 develops the Hallén and Pocklington integral equations for determining the current on a linear antenna, discusses King's three-term approximations, and then concentrates on numerical solutions for delta-gap input and arbitrary incident fields. We discuss the method of moments, implemented with the exact or the approximate thin-wire kernel and using various bases, such as pulse, triangular, and NEC bases. These methods require the accurate evaluation of the exact thin-wire kernel, which we approach using an elliptic function representation.

In Chapter 22 we discuss coupled antennas, in particular, parallel dipoles. Initially, we assume sinusoidal currents and reduce the problem to the calculation of the mutual impedance matrix. Then, we consider a more general formulation that requires the solution of a system of coupled Hallén equations. We present various examples, including the design of Yagi-Uda antennas.

Our MATLAB-based numerical solutions are not meant to replace sophisticated commercial field solvers. The inclusion of numerical methods in this book was motivated by the desire to provide the reader with some simple tools for self-study and experimentation. The study of numerical methods in electromagnetics is a subject in itself and our treatment does not do justice to it. However, we felt that it would be fun to be able to quickly compute fairly accurate radiation patterns in various antenna examples, such as Yagi-Uda and other coupled antennas, as well horns and reflector antennas.

The appendix includes summaries of physical constants, electromagnetic frequency bands, vector identities, integral theorems, Green's functions, coordinate systems, Fresnel integrals, sine and cosine integrals, the stationary phase approximation, Gauss-Legendre quadrature, Lorentz transformations, and a detailed list of the MATLAB functions.

Finally, there is a large (but inevitably incomplete) list of references, arranged by topic area, as well as several web links, that we hope could serve as a starting point for further study.

MATLAB Toolbox

The text makes extensive use of MATLAB. We have developed an "Electromagnetic Waves & Antennas" toolbox containing 170 MATLAB functions for carrying out all of the computations and simulation examples in the text. Code segments illustrating the usage of these functions are found throughout the book, and serve as a user manual. The functions may be grouped into the following categories:

1. Design and analysis of multilayer film structures, including antireflection coatings, polarizers, omnidirectional mirrors, narrow-band transmission filters, surface plasmon resonance, birefringent multilayer films and giant birefringent optics.
2. Design of quarter-wavelength impedance transformers and other impedance matching methods, such as Chebyshev transformers, dual-band transformers, stub matching and L-, Π- and T-section reactive matching networks.
3. Design and analysis of transmission lines and waveguides, such as microstrip lines and dielectric slab guides.
4. S-parameter functions for gain computations, Smith chart generation, stability, gain, and noise-figure circles, simultaneous conjugate matching, and microwave amplifier design.
5. Functions for the computation of directivities and gain patterns of linear antennas, such as dipole, vee, rhombic, and traveling-wave antennas, including functions for the input impedance of dipoles.
6. Aperture antenna functions for open-ended waveguides, horn antenna design, diffraction integrals, and knife-edge diffraction coefficients.
7. Antenna array design functions for uniform, binomial, Dolph-Chebyshev, Taylor one-parameter, Taylor $\bar{n}$ distribution, prolate, Villeneuve arrays, sector-beam,

multi-beam, Woodward-Lawson, and Butler beams. Functions for beamwidth and directivity calculations, and for steering and scanning arrays.

8. Numerical methods for solving the Hallén and Pocklington integral equations for single and coupled antennas, computing the exact thin-wire kernel, and computing self and mutual impedances.
9. Several functions for making azimuthal and polar plots of antenna and array gain patterns in decibels and absolute units.
10. There are also several MATLAB movies showing pulse propagation in dispersive media illustrating slow, fast, and negative group velocity; the propagation of step signals and pulses on terminated transmission lines; the propagation on cascaded lines; step signals getting reflected from reactive terminations; fault location by TDR; crosstalk signals propagating on coupled lines; and the time-evolution of the field lines radiated by a Hertzian dipole.

    The MATLAB functions as well as other information about the book may be downloaded from the web page:

    `http://www.ece.rutgers.edu/~orfanidi/ewa`

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