

*Electromagnetic
Waves and Antennas*

Electromagnetic Waves and Antennas

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To Monica, John and Anna

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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.
- Waveguiding systems, including metallic, dielectric, and surface waveguides, transmission lines, impedance matching, and S -parameters.
- Linear and aperture antennas, scalar and vector diffraction theory, plane-wave spectrum, Fourier optics, superdirectivity and superresolution concepts, 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

Chapters 1–8 develop waves concepts and applications, progressing 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 and polarizers.

Also discussed are pulse propagation in dispersive media, group and front velocities, causality, group velocity dispersion, spreading and chirping, dispersion compensation, slow, fast, and negative group velocity, an introduction to chirp radar and pulse compression, as well as, ray tracing and atmospheric refraction, inhomogeneous waves, total internal reflection, surface plasmon resonance, Snell’s law and perfect lenses in negative-index media.

Chapters 9–10 deal with metallic waveguides, dielectric waveguides and optical fibers, and plasmonic surface waveguides, including Sommerfeld and Goubau lines in which there is renewed interest for THz applications.

Chapters 11–13 are on transmission lines, microstrip and coaxial lines, terminated lines, standing wave ratio and the Smith chart, and examples of time-domain transient response of lines, coupled lines and crosstalk, and coupled mode theory and fiber Bragg gratings, as well impedance matching methods, which include multisection transformers, quarter-wavelength transformers with series or shunt stubs, single, double, and triple stub tuners, as well as L -section and II -section reactive matching networks.

Chapter 14 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 cir-

cles, illustrating the concepts with a number of low-noise high-gain microwave amplifier designs including the design of input and output matching circuits.

Chapters 15–25 deal with radiation and antennas. Chapters 15–16 include 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.

In Chapter 17, we discuss a number of linear antenna examples, such as Hertzian and half-wave dipoles, traveling, vee, and rhombic antennas, as well as loop antennas.

Chapters 18–20 are devoted to radiation from apertures and diffraction, 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, and geometrical theory of diffraction.

The equivalence of the plane-wave spectrum point of view of diffraction and its equivalence to the Rayleigh-Sommerfeld diffraction theory is developed in Chapter 19, both for scalar and vector fields including Smythe diffraction integrals, apertures in conducting screens, Bethe-Bouwkamp theory of diffraction by small holes, and the Babinet principle for scalar and electromagnetic fields.

Chapter 20 continues the discussion of diffraction concepts, with emphasis on Fourier optics concepts, Fresnel approximation, Talbot effect, Fourier transformation properties of lenses, one- and two-dimensional apodizer design and aperture synthesis for narrow beamwidths and low sidelobes including Fourier-Bessel and Dini series expansions, realization of apodizers using star-shaped masks, coronagraphs and starshade occulters, superresolving apertures, and ending with an overview of superdirectivity, superresolution, and superoscillation concepts based on prolate spheroidal wave functions.

Chapter 21 presents a number of aperture antenna examples, such as open-ended waveguides, horn antennas, including optimum horn designs, microstrip antennas, parabolic and dual reflectors, and lens antennas.

Chapters 22–23 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 includes 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 discuss the analogies with time-domain DSP and digital filter design methods, such as Butler beams which are equivalent to the FFT.

Chapters 24–25 deal with numerical methods for linear antennas. Chapter 24 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. We also discuss coupled antennas, parallel dipoles, and their mutual impedance matrix, and more generally, the solution of coupled Hallén equations, including the design of Yagi-Uda 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, stationary-phase approximation, Gauss-Legendre quadrature, tanh-sinh double-exponential quadrature, an extensive review of prolate spheroidal wave functions including MATLAB functions for their computation, Lorentz transformations, and a detailed list of the book's MATLAB functions.

Finally, there is a large (but inevitably incomplete) list of references, arranged by topic area, 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 about 200 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.

Our MATLAB-based numerical solutions are not meant to replace sophisticated commercial field solvers. The study of numerical methods in electromagnetics is a subject in itself and our treatment does not do justice to it.

The inclusion of numerical methods was motivated by the desire to provide the reader with some simple tools for self-study and experimentation. We felt that it would be useful and fun to be able to quickly carry out the computations illustrating various waves and antenna applications, and have included enough MATLAB code in each example (but skipping all figure annotations) that would enable the reader to reproduce the results. 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, and birefringent multilayer films.
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, dielectric slab guides, plasmonic waveguides, Sommerfeld wire, and Goubau lines.
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, and horn antenna design.
7. Functions for diffraction calculations, such as diffraction integrals, and knife-edge diffraction coefficients, Talbot effect, Bethe-Bouwkamp model.
8. One- and two-dimensional apodizer design for continuous aperture distributions, optimum prolate apodizers, Taylor's one-parameter and \bar{n} -bar one-dimensional distributions, and their two-dimensional versions.

9. 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.
10. 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.
11. Several functions for making azimuthal and polar plots of antenna and array gain patterns.
12. 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 book's web page:

<http://www.ece.rutgers.edu/~orfanidi/ewa>

Acknowledgements

I would like to thank the many generations of my students who shaped the content of this book and the following people for their feedback, useful comments, and suggestions for improvement: M. Abouowf, S. Adhikari, L. Alekseyev, P. Apostolov, F. Avino, S. Bang, R. Balder-Navarro, V. Borisov, F. Broyde, K-S. Chen, C. Christodoulou, C. Collister, A. Dana, S. Datta, A. Davoyan, N. Derby, S. Diedenhofen, G. Fano, H. Fluhler, K. Foster, S. Fuhrman, C. Gutierrez, J. Heeb, J. Hudson, C-I. G. Hsu, R. Ianconescu, F. Innes, M. Jabbari, H. Karlsson, S. Kaul, M. Kleijnen, J. Krieger, W. G. Krische, H. Kumano, A. Lakshmanan, R. Larice, E. M. Lau, R. Leone, M. Maybell, P. Matusov, K. T. McDonald, K. Michalski, J-S. Neron, F. Nievinski, V. Niziev, F. D. Nunes, H. Park, U. Paz, E. Perrin, A. Perrin, D. Phillips, K. Purchase, D. Ramaccia, G. Reali, R. Rosensweig, T. K. Sarkar, M. Schuh, A. Siegman, P. Simon, K. Subramanian, L. Tarof, L. M. Tomás, A. Toscano, E. Tsilioukas, V. Turkovic, Y. Vives, T. Weldon, G. Weiss, P. Whiteneir, A. Young, D. Zhang, C. Zarowski, and G. Zenger. Any errors or shortcomings are entirely my own.

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July 2016