Electromagnetic Theory and Plasmonics for Engineers

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Preface

This book is created on the basis of lectures on electromagnetic (EM) field theory for Erasmus undergraduate (BA degree) students at Vilnius Gediminas Technical University (VGTU), Lithuania, and on the basis of lectures for Ph.D. students at Linköping University, Sweden.

Some calculations in Chaps. 7 and 8 were completed for BA degree practice at VGTU by Dr. Artūras Bubnelis.

A number of calculations in Chap. 9 were carried out for a BA degree at VGTU by Engineer Ekaterina Nadopta.

This book focuses on physics and microwave theory based on Maxwell's equations and boundary conditions which are important for studying the operation of waveguides and resonators in the wide frequency range, namely, from about 10^9 to 10^{16} hertz (Hz). This book contains such main topics as the interaction of EM waves with different substances, plane EM wave propagation, reflection and transmission thereof, boundary value problems, solutions of Maxwell's equations under certain boundary conditions, dispersion equations, behaviors of waveguide modes as transverse electric and magnetic ones, surface plasmon polariton mode as well as oscillations in resonators, etc. Taking into account the fact that the operation of all electrical, electronic, and plasmonic devices is based on the knowledge of the EM field theory, the study of the subject gives a powerful tool for understanding the operation of any EM device.

During the last decades, the development of the EM field theory was basically carried out in two directions, namely developing microwave devices as well as developing devices on the basis of optic laws due to the formal point of view since light is actually an EM wave, and the Maxwell's equations with the corresponding boundary conditions can thoroughly describe optical phenomena.

Throughout history, the development of microwave waveguide and antenna technologies evolved from relatively low frequencies (radio and microwave frequencies) to higher ones. Here the frequency measurement is traditionally made in Hz (as well as in multiple Hz units such as GHz, THz, and PHz).

Historically, optical devices operate at relatively high frequencies (infrared (0.3 THz–0.43 PHz), visible (0.43–0.79) PHz, and ultraviolet (0.79–30) PHz), and there is a tendency to develop devices that can also operate at lower frequencies. The optics was the basis for successful development of such advanced scientific research area as plasmonics and photonics. Therefore, in plasmonics, which we will be considering in this book, the measurement of frequency usually occurs in Hz (hertz), eV (electron volt), cm^{-1} (centimeter to the power mines one), and K (kelvin)—as in optics.

In this way, we see a different approach in microwave and optical studies even in frequency units. So the terminology and approaches to EM problems used in microwave theory and plasmonics (optics) may differ. Here we note a few differences important for the book:

(1) Since this book contains plasmonics, we wish to note that everywhere the dispersion characteristics are depicted in a way which is accepted in the microwave theory (electrodynamics), i.e., propagation constants are located on the ordinate axis and frequencies are placed on the abscissa axis.
(2) Dependences on time and longitudinal propagation constant are also usually taken into account in technical literature by different multiplier $e^{i(\omega t - hz)}$in electrodynamics and $e^{i(hz - \omega t)}$ in optics. Due to differentiation, this difference leads to non-matching signs in some expressions of intermediate values.
(3) The approach to the definition of circular right- and left-polarized waves in electrodynamics and optics is also different. In this book, we have chosen the approach recommended by the Institute of Electrical and Electronic Engineers (IEEE) for the engineering community.

Being aware of the large workload of students and specialists as well as significant volume of material for studies, the author gives detailed explanations of derivation of many expressions.

The book can be useful for Erasmus students with English language as a foreign language; therefore, the author sometimes additionally gives the synonyms of a word (in round brackets) which are possible to use for the specific item under analysis.

Chapter 6 can be of particular use for specialists in Telecommunications Engineering since this chapter presents a detailed analysis of various questions about polarization of reflected waves from dielectric and metal surfaces. The contents of this chapter cover issues encountered by Prof. L. Nickelson while implementing the project for the Communications Regulatory Authority of the Republic of Lithuania.

This book *sometimes* presents several equivalent terminologies related to the same value or to the same phenomena used nowadays. This may assist in gaining a rapid understanding of technical literature as articles use a wide range of terminologies.

The main motivation for writing this book was the author's wish to pass the knowledge accumulated throughout a span of approximately 50 years on to those who are now starting their studies in the EM field theory.

Field research activities of author: Electromagnetic field theory and application thereof to various physical and engineering problems. She with co-authors developed methods based on the Theory of Singular Integral Equations with the help of which two-dimensional and three-dimensional waveguides and structures with very complicated topology can be calculated. Prof. L. Nickelson has also researched different-layered waveguides containing strong lossy materials such as metamaterials, onion-like carbon, silicon carbide (SiC), gyrotropy plasma. Together with co-authors, she has published the total of five books, including this one, and plus two chapters of INTECH books, eight patents, and more than 100 articles.

It is also important to note the principle of formula numbering in this textbook. The first digit of numbering corresponds to the number of certain chapter while the second digit indicates the section number of that chapter and the third digit corresponds to the number of the formula in this section. For example, if we take formula (3.9.7), the digit "3" represents the third chapter, the digit "9" means the ninth section, and the digit "7" signifies the seventh formula in Sect. 9.

Vilnius, Lithuania Liudmila Nickelson

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I am very thankful to Dr. Artūras Bubnelis who let me use his BA degree practice results in Chaps. 7 and 8 of this textbook.

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Contents

Abbreviations

1D	One dimension
2D	Two dimensions
3D	Three dimensions
a.r.	Atomic radius
a.u.	Atomic units
AC	Alternating current
Chap.	Chapter
Chaps.	Chapters
dB	Decibel
DC	Direct current
DIN	German institute for standardization
e.g.	For example
EHF	Extremely high frequency (30–300 GHz)
EHz	Exahertz (10^{18} Hz)
EM	Electromagnetic
etc.	Et cetera, continuing in the same way
eV	Electron volt
Fig.	Figure
Figs.	Figures
Hz	Hertz, unit of frequency
i.e.	“that is” (id est)
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared range f $\sim$ 0.3–430 THz
ISO	Internal System of Quantity
ITU	International Telecommunications Union
K	Kelvin
KHz	Kilohertz (10^3 Hz)
LDF	London dispersion forces
LF	Low frequency (30–300 kHz)
LSPs	Localized surface plasmons

m	Meter is unit of length
MHz	Megahertz (10^6 Hz)
mm	Millimeter (10^{-3} m)
nm	Nanometer (10^{-9} m)
Np	Neper
PEC	Perfect electric conductor
PHz	Petahertz (10^{15} Hz)
pm	Picometers (10^{-12} m)
RF	Radio frequency (20 kHz–300 GHz)
s	Second, unit of time
SERS	Surface-enhanced Raman scattering spectroscopy
SHF	Super high frequency (3–30 GHz)
SI units	International System of Units
SPPs	Surface plasmon polaritons
SPR	Surface plasmon resonance
TE	Transverse electric
TEM	Transverse electromagnetic
THF	Tremendously high frequency (300–3000 GHz)
THz	Terahertz (10^{12} Hz)
TIRE	Total internal reflection ellipsometry
TM	Transverse magnetic
UV	Ultraviolet ($\sim$0.79–30 PHz)
VGTU	Vilnius Gediminas Technical University
VIS	Visible range ($\sim$0.43–0.79 PHz)
viz.	"namely," "that is to say"
μm	Micrometer (10^{-6} m)

Abstract

The textbook *Electromagnetic Theory and Plasmonics for Engineers* (L. Nickelson) contains nine chapters, 51 tables, more than 350 figures and 2000 formulae, 749 pages.

This textbook focuses on physics and microwave theory based on Maxwell's equations and boundary conditions which are important for the purposes of studying the operation of waveguides and resonators in wide frequency range, namely, from approx. 10^9 to 10^{16} hertz. This textbook includes physical explanations of electromagnetic (EM) phenomena and explores the derivation of most expressions of physical quantities in great detail. The chapter about plasmonics is written in a style characteristic for microwave electrodynamics.

The textbook has a fairly large number of figures and tables to ease the understanding of the topics discussed therein. In addition, there are numerous review questions after each chapter. The main topic of this textbook is the propagation of EM waves on waveguides or surfaces (Chaps. 7–9). All previous chapters prepare the reader for a more in-depth understanding of these last three chapters.

Keywords Electromagnetics · Plasmonics · Electromagnetic waves
Maxwell's equations · Boundary conditions · Constitutive relations
Dispersion equations · Dielectrics · Conductors · Complex media
Lossy media · Permittivity · Permeability · Linearly polarized EM waves
Circularly polarized waves · Elliptically polarized waves · Standing wave
Incident wave · Reflected wave · Refracted wave · Perpendicular and parallel polarized waves · Phase and group velocities · Hollow metallic waveguides
Propagation constant · Complex amplitudes · Phase constant · Attenuation constant · Impedance · Cavity resonator · TE mode · TM mode
Surface plasmon polaritons · SPP waves · Cylinder and flat metal interface
Mode excitations · Conduction current · Displacement current · Skin depth
Cutoff frequency