

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.

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Contents

1	Vector Analysis in Annex to Electromagnetics	1
1.1	Introduction to Vector Analysis	1
1.2	Basic Vector Operations	3
1.2.1	Unit Vectors	5
1.2.2	Addition of Two Vectors	6
1.2.3	Base Vectors and Vector Components	9
1.2.4	Vectors in Three Dimensions	10
1.2.5	Rectangular Components in 2D	10
1.2.6	Position and Displacement Vectors	11
1.2.7	Vector Transform	14
1.2.8	Dot Product of Two Vectors	15
1.2.9	Cross Product of Two Vectors	18
1.2.10	Triple Products	20
1.3	Differential and Integral Calculus	22
1.3.1	Differential Length Vector	23
1.3.2	Differential Surface Vector	24
1.3.3	Total and Partial Derivatives	25
1.3.4	The Operator ∇	26
1.3.5	Gradient of a Scalar Field	27
1.3.6	Divergence of a Vector Field and Divergence Theorem	31
1.3.7	Curl of a Vector Field and Stokes' Theorem	34
1.4	Complex Numbers	35
1.4.1	Geometric Representation of the Complex Numbers	37
1.4.2	Trigonometric Form of the Complex Numbers	37
1.4.3	Cross and Dot Products of Two Complex Numbers	40
1.5	Examples and Problems	42
1.6	Review Questions	48

2	Static and Stationary Fields	51
2.1	Introduction	51
2.2	Basic Classification of Fields	54
2.2.1	General Definitions	54
2.2.2	Distinction Between Stationary and Static Fields	56
2.2.3	Fields and Examples	56
2.2.4	Main Expressions for Stationary and Static Fields	58
2.3	Basis Laws and Concepts of Electrostatics	59
2.3.1	About Electrostatic Fields	60
2.4	Electric Charge	61
2.5	Force Between Electric Charges and Coulomb's Law	63
2.6	Electric Field	67
2.7	Electrostatic Potential	71
2.8	Gradient of Electrostatic Potential	73
2.9	Electric Flux, Electric Flux Density and Gauss's Law	75
2.9.1	Divergence of Electrostatic Field	77
2.9.2	Curl of Electrostatic Field	78
2.10	Divergence of Electric Flux Density	78
2.11	Work and Potential Energy in Electrostatics	80
2.12	Electrostatic Potential Energy	82
2.13	Laplace's and Poisson's Equations	84
2.14	Stationary-in-Time Fields Arising of Steady Current	85
2.15	Examples and Problems	87
2.16	Review Questions	94
3	Fields and Materials	97
3.1	Introduction	97
3.2	Dielectrics and Polarization	101
3.2.1	Electric Polarization and Dipole Moment	102
3.2.2	Polarization of Nonpolar Dielectrics	103
3.2.3	Polarization of Polar Dielectrics	104
3.2.4	Electrostatic Attraction and Repulsion Forces	105
3.2.5	Polarizability	107
3.3	Atomic Structure of Linear Dielectrics	108
3.3.1	Nonpolar and Polar Covalent Bonds	108
3.3.2	Ionic Bonds	110
3.4	Types of Dielectric Polarization	113
3.5	Polarization Mechanisms	114
3.5.1	Electronic Polarization	114
3.5.2	Atomic Polarization	115
3.5.3	Ionic Polarization	115
3.5.4	Dipolar Polarization	116
3.5.5	Predominant Type of Polarization Depending on the Range of Frequencies	118

- 3.6 Electric Flux Density, Permittivity, and Susceptibility 119
- 3.7 Relationships Between Volume Charge Densities 122
- 3.8 Electric Fields Created by Free and Bound Charges 123
- 3.9 Electric Field into a Dielectric Insert 124
 - 3.9.1 Examples of Extraneous Charges 125
 - 3.9.2 Surface Charge Density 126
 - 3.9.3 Electric Field in Dielectric Insert Placed Between Two
Plates of a Capacitor 127
 - 3.9.4 Consideration of Non-uniform Polarization 128
- 3.10 Relative Permittivity 130
- 3.11 Complex Permittivity 132
- 3.12 Displacement and Polarization Currents 136
- 3.13 Notes About Electric Currents 138
 - 3.13.1 Conduction Currents 139
 - 3.13.2 Convection Currents 141
 - 3.13.3 Advection Currents 142
 - 3.13.4 Eddy Currents 143
 - 3.13.5 Electrolytic Currents 144
 - 3.13.6 Magnetization Currents 144
- 3.14 Ohm’s Law 145
 - 3.14.1 Extraneous Currents and Forces 148
 - 3.14.2 Electromotive Force 150
 - 3.14.3 Magnetomotive Force 152
- 3.15 Electrical Conductivity and Resistivity 153
- 3.16 Magnetic Field Sources and Concepts 155
 - 3.16.1 Right-Hand Grip Rule 157
 - 3.16.2 Left-Hand Rule 158
- 3.17 Postulates of Magnetostatics in Free Space 159
- 3.18 Ampere’s Law 160
- 3.19 Magnetic Field Intensity and Magnetic Susceptibility 163
- 3.20 Boundary Conditions for Steady Electric Current Density 166
- 3.21 Scalar and Vector Potentials 169
- 3.22 Magnetization 170
- 3.23 Biot–Savart Law 174
- 3.24 Magnetic Flux Density Around a Straight Wire 175
- 3.25 Magnetic Flux Density Due to Circular Current Loops 177
- 3.26 Main Types of Magnetic Materials 180
 - 3.26.1 Diamagnetism 181
 - 3.26.2 Paramagnetism 182
 - 3.26.3 Ferromagnetism 183
 - 3.26.4 Ferrimagnetism 184
 - 3.26.5 Antiferromagnetism 184

3.27	Constitutive Relations for Media	185
3.27.1	Isotropic Media	187
3.27.2	Anisotropic Media	188
3.27.3	Permittivity Tensor of Crystals	190
3.27.4	Biisotropic Media	190
3.27.5	Bianisotropic Media	191
3.27.6	Notes About Media	191
3.28	Review Questions	192
4	Maxwell's Equations and Boundary Conditions	195
4.1	Introduction	195
4.2	Faraday's Law of Electromagnetic Induction	197
4.2.1	Fundamental Postulate for Electromagnetic Induction	198
4.2.2	Lenz's Law	200
4.3	Maxwell's Equations	201
4.3.1	Maxwell's Equations in Differential Form	201
4.3.2	The Sense of Maxwell's Equations	202
4.3.3	Co-dependence of Maxwell's Equations	203
4.3.4	Maxwell's Equations in Large-Scale Form	205
4.3.5	Faraday's Law in Integral Form	206
4.3.6	Ampere's Law in Integral Form	206
4.3.7	Gauss's Law	208
4.3.8	Magnetic Source Law	209
4.3.9	Table of Maxwell's Equations	210
4.4	Maxwell's Equations for the Time-Periodic Case	211
4.5	Source-Free Fields in Nonconducting Media	213
4.6	Classification of Media Based on the Conductivity	215
4.7	Concept of Boundary Conditions	219
4.8	Derivation of Electromagnetic Boundary Conditions	220
4.9	Boundary Conditions for \mathbf{E}_t and \mathbf{D}_t Components	222
4.10	Boundary Conditions for \mathbf{H}_t and \mathbf{B}_t Components	228
4.11	Boundary Conditions for \mathbf{D}_n and \mathbf{E}_n Components	231
4.11.1	Explanation About Surface Charges on Interface of Dielectrics	233
4.11.2	Boundary Conditions for Polarization Vectors	235
4.12	Boundary Conditions for \mathbf{B}_n and \mathbf{H}_n Components	236
4.13	Deformation of \mathbf{E} and \mathbf{D} Vectors at a Dielectric Sphere Boundary	237
4.13.1	Solution for the Radial Part of Differential Equation	241
4.13.2	Solution for the Angular Part of Differential Equation	241

- 4.13.3 Constructing of the General Solution 242
- 4.13.4 Satisfying of Boundary Condition 243
- 4.13.5 Potentials Inside and Outside the Sphere 246
- 4.13.6 Electric Field Inside and Outside the Sphere and
Bounded Surface Charges 247
- 4.13.7 Force Lines of Electric Field and Electric
Flux Density 249
- 4.14 Boundary Conditions for **E** and **D** in Pictures 251
- 4.15 Boundary Conditions for **H** and **B** in Pictures 256
- 4.16 Summarizing Boundary Conditions Between
Lossless Dielectrics 260
- 4.17 Boundary Conditions for Dielectric-Conductor 262
 - 4.17.1 Boundary Condition at the Interface of Two
Conductor Media 266
- 4.18 Review Questions 266
- 5 Plane Electromagnetic Wave Propagation 269**
 - 5.1 Introduction 269
 - 5.2 Phase Shift—Leading and Lagging Phases of
Electromagnetic Waves 273
 - 5.3 Spherical and Cylindrical Electromagnetic Waves 277
 - 5.4 Plane Waves 280
 - 5.4.1 Relations Between Electric and Magnetic Fields of a
Plane Wave in a Vacuum 288
 - 5.5 Complex Amplitudes and Attenuation Constant 289
 - 5.6 Presentation of Maxwell’s Equations for Plane Waves 291
 - 5.7 Intrinsic Impedance 292
 - 5.8 Time-Periodic Case for a Plane Wave 296
 - 5.9 Plane Waves in Lossy Media 298
 - 5.10 Plane Waves in Good Conductors 303
 - 5.10.1 Phase Difference Between **E** and **H** Fields in Good
Conductors 308
 - 5.11 Plane Waves in Low-Loss Dielectrics 309
 - 5.12 Flow of Electromagnetic Power and the Poynting Vector 310
 - 5.12.1 Poynting’s Theorem 314
 - 5.13 Time-Averaged Poynting Vector 315
 - 5.14 Phase and Group Velocity 319
 - 5.15 Polarization of Electromagnetic Waves 326
 - 5.15.1 Constructive and Destructive Interference 327
 - 5.16 Plane Wave and Polarization 328
 - 5.16.1 Common Notes About Polarization of Electromagnetic
Waves 332
 - 5.17 Approach to Polarization from Electrodynamics and Optics 333

5.18	Linear Polarization	338
5.19	Circularly Polarized Wave	340
5.20	Elliptically Polarized Wave	340
5.20.1	Polarization Ellipse	341
5.21	General Description of Polarizations	346
5.21.1	Shape of Curve Drawn by the End of E-Vector Depending on the Phase Shift	351
5.22	Problem Related to Linear Polarization of Electromagnetic Waves	352
5.23	Problem Related to Circular Polarization of Electromagnetic Waves	354
5.24	Problem Related to Elliptical Polarization of Electromagnetic Waves	356
5.25	Standing Electromagnetic Waves	358
5.26	Review Questions	360
6	Reflection and Transmission of Plane Electromagnetic Waves	363
6.1	Introduction	363
6.2	Main Definitions About Incident Plane Waves	365
6.2.1	Perpendicular and Parallel Polarizations	367
6.2.2	Perpendicular Polarization	371
6.2.3	Parallel Polarization	371
6.3	Fresnel's Equations	372
6.4	Total Internal Reflection and Critical Angle	376
6.5	Brewster's Angle	379
6.6	Determination of a Phase of Reflected Wave	380
6.7	Oblique Incidence of Perpendicular Polarized Wave on Dielectric Interface	388
6.8	Oblique Incidence of Parallel Polarized Wave on Dielectric Interface	392
6.9	Normal Incidence of Parallel Polarized Wave on Dielectric Interface	395
6.10	Normal Incidence of Parallel Polarized Wave on Conductor Plane	400
6.10.1	Calculations of Electric and Magnetic Fields of Standing Waves	405
6.11	Oblique Incidence of Perpendicular Polarized Waves on Conducting Plane	407
6.11.1	Determination of the Phase of Reflected Wave from a Perfect Conductor Plane	410
6.11.2	Distributions of Total Magnetic Field	411
6.11.3	Pattern of Electromagnetic Field and Current Allocations	412

- 6.12 Oblique Incidence of Parallel Polarized Waves on Conducting Plane 414
 - 6.12.1 Phase Velocity of Electromagnetic Waves Directed by the Conducting Plane 418
 - 6.12.2 Distributions of Total Electric Field 419
 - 6.12.3 Pattern of Electromagnetic Field, Current and Charge Allocations 420
- 6.13 Types of Waves Propagating Between Two Conductor Planes 422
- 6.14 Review Questions 423
- 7 Rectangular Hollow Metallic Waveguides and Resonators 425**
 - 7.1 Introduction 425
 - 7.2 Classification of Propagating Modes 426
 - 7.3 Electromagnetic Wave Propagation in a Source-Free Area 429
 - 7.4 General Characteristics of Waveguide Modes 430
 - 7.4.1 Helmholtz’s Equations 433
 - 7.4.2 TEM Modes 437
 - 7.5 General Behaviors of TE and TM Modes 440
 - 7.5.1 Transverse Electric Modes 441
 - 7.5.2 Transverse Magnetic Modes 443
 - 7.5.3 Expressions Corresponding to TE and TM Modes 445
 - 7.5.4 A Cutoff Frequency and Wavelength of Waveguide Modes 445
 - 7.5.5 Phase and Group Velocities of Propagating Modes 449
 - 7.5.6 Wave Impedance of TE and TM Modes 450
 - 7.6 Solutions for TE_{mn} Modes 452
 - 7.6.1 Instantaneous Field Expressions for TE_{mn} Modes 459
 - 7.6.2 Explanation of TE_{mn} Mode Indexes 460
 - 7.6.3 Dispersion Characteristics and Cutoff Frequencies of TE_{mn} Modes 462
 - 7.6.4 Main Mode TE_{10} of a Rectangular Waveguide 464
 - 7.6.5 Poynting Vector and Energy Transportation of TE_{10} Mode 466
 - 7.6.6 Calculations of Electric and Magnetic Field Vectors 467
 - 7.6.7 Distribution of Surface Conduction Currents of TE_{10} Mode 471
 - 7.6.8 3D Distribution of Electric Field Intensity of TE_{10} Mode 472
 - 7.6.9 Displacement and Surface Conduction Currents 473
 - 7.6.10 Schematic Sectional View for TE_{10} 475

- 7.7 Solutions for TM_{mn} Modes 477
 - 7.7.1 Instantaneous Field Expressions for TM_{mn} Modes 481
 - 7.7.2 Explanation of TM_{mn} Mode Indexes 482
 - 7.7.3 Dispersion Characteristics and Cutoff Frequency of TM_{mn} Modes 483
 - 7.7.4 Joint Dispersion Characteristics of TE_{mn} and TM_{mn} Modes 485
 - 7.7.5 Calculations of Electric and Magnetic Fields of TM_{11} Mode 485
 - 7.7.6 Distribution of Surface Conduction Currents of TM_{11} Mode 487
 - 7.7.7 3D Distribution of Electric Field Intensity of TM_{11} Mode 489
 - 7.7.8 Schematic Sectional View for TM_{11} Mode 490
- 7.8 Attenuation in Rectangular Waveguides 491
 - 7.8.1 Attenuation by a Filled Waveguide Dielectric 492
 - 7.8.2 Attenuation by Conducting Waveguide Walls 494
- 7.9 Excitation of Waveguides by Probes, Loops, and Slots 497
 - 7.9.1 Excitation by a Probe 498
 - 7.9.2 Excitation by a Loop 500
 - 7.9.3 Excitation by a Slot 501
- 7.10 Rectangular Cavity Resonators 503
 - 7.10.1 Common Principles About Resonators 504
 - 7.10.2 Transverse Electric TE_{mnp} Modes 510
 - 7.10.3 Resonance Frequency of TE_{mnp} Mode 517
 - 7.10.4 Schematic Sectional View of TE_{101} Mode 522
- 7.11 Transverse Magnetic TM_{mnp} Resonator Modes 523
 - 7.11.1 Resonance Frequency of TM_{mnp} Mode 529
 - 7.11.2 Transverse Magnetic TM_{111} Mode 532
 - 7.11.3 Schematic Sectional View for TM_{111} Mode 534
- 7.12 Quality Factor 535
- 7.13 Excitation of Rectangular Resonators by Probes, Loops, and Slots 538
- 7.14 Conclusions About Resonators 539
- 7.15 Examples and Problems 540
- 7.16 Review Questions 542
- 8 Cylindrical Hollow Metallic Waveguides and Cavity Resonators 545**
 - 8.1 Introduction 545
 - 8.2 Solution of Helmholtz’s Equation in Cylindrical Coordinates 547
 - 8.3 Bessel Functions and Their Properties 552
 - 8.4 Solutions for TE_{mn} Modes in Circular Waveguides 556
 - 8.5 Instantaneous Field Expressions for TE_{mn} Modes 559

8.6	Explanation of TE_{mn} Mode Indexes	560
8.7	Expressions Corresponding to Transverse Electric Modes	562
8.8	Dispersion Characteristics of TE_{mn} Modes	563
8.9	Main Mode TE_{11} of Cylindrical Waveguides	563
8.10	Electromagnetic Field Distributions of TE_{11} Mode	565
8.11	Schematic Sectional Views for TE_{11} Mode	567
8.12	Solutions of Helmholtz's Equation for TE_{mn} Modes	569
8.13	Instantaneous Field Expressions for TM_{mn} Modes	571
8.14	Explanation of TM_{mn} Mode Indexes	572
8.15	Expressions Corresponding to Transverse Magnetic Modes	573
8.16	Dispersion Characteristics and Cutoff Frequency of TM_{mn} Modes	575
8.17	Joint Dispersion Characteristics of TE_{mn} and TM_{mn} Modes	576
8.18	Formulae for TM_{01} Mode	576
8.19	Calculation of TM_{01} Field Distributions	578
8.20	Schematic Sectional Views for TM_{01} Mode	579
8.21	Circular Cylindrical Cavity Resonators	581
8.22	Expressions for Electromagnetic Field Components of TE_{mnp} Modes	583
8.23	Instantaneous Field Expressions for Resonator TE_{mnp} Modes	586
8.24	Resonance Frequency of TE_{mnp} Modes	587
8.25	Electromagnetic Field Calculations of TE_{111} Mode	587
8.26	Schematic Sectional Views of TE_{111} Mode	592
8.27	Transverse Magnetic TM_{mnp} Resonator Modes	594
8.28	Instantaneous Field Expressions for Resonator TM_{mnp} Modes	597
8.29	Resonance Frequency of TM_{mnp} Modes	597
8.30	Resonator Mode TM_{010}	598
8.31	Calculations of TM_{011} Field Distributions	600
8.32	Schematic Sectional View of TM_{011}	604
8.33	Review Questions	607
9	Plasmonics	611
9.1	Introduction	611
9.2	Chronological Development of Plasmonics	612
9.3	Definitions Used in Plasmonics	616
9.4	General Concepts of Plasmonics	619
9.4.1	Dispersion Equations for Two Types of Electromagnetic Waves	621
9.4.2	Plasmons with the Longitudinal Component of Electric Field	623
9.4.3	High- and Low-Frequency Plasmons	625

9.4.4	Plasmons in Complex Media	626
9.5	Optical Properties of Metals	627
9.6	Models of Dielectric Permittivity Determination	629
9.6.1	Drude and Drude–Sommerfeld Models	630
9.6.2	Dependence of Current Density on the Loss Term	633
9.6.3	Solution of Homogeneous Differential Equation	634
9.6.4	Case When the Electric Field Is a Stationary Field	635
9.6.5	Case When the External Electromagnetic Field Is a Time-Harmonic Monochromatic	636
9.6.6	Notes About the Conductivity	641
9.6.7	Realization of Drude–Sommerfeld Model	642
9.7	Drude–Lorentz Model	643
9.7.1	Harmonic Oscillators	644
9.8	Determination of Permittivity by the Drude–Lorentz Model	645
9.9	Debye Model	648
9.10	Volume Plasmons in “Jelly” Model	649
9.11	Surface Plasmon Polariton at a Flat Metal Interface	654
9.11.1	General Characteristics of SPPs	654
9.12	Dispersion Equations of SPPs at a Flat Interface	660
9.12.1	TM and TE Mode Components	663
9.12.2	Helmholtz’s Equations for TM and TE Modes	664
9.12.3	Solution and Dispersion Equation for TM Modes	665
9.12.4	Solution for TE Modes and Dispersion Equation	669
9.13	Dispersion Equations of Conducting Cylindrical Waveguides	671
9.14	Principles of SPPs Excitations	682
9.15	Application of Plasmonic Phenomena	685
9.16	Examples and Problems	688
9.16.1	Drude–Sommerfeld Model	689
9.16.2	Dispersion Characteristics of SPP Mode at Au and Ag Flat Interfaces	690
9.16.3	Dispersion Characteristics of Au Cylindrical Waveguides	693
9.17	Review Questions	694
	List of Appendixes	697
	Brief CV of Prof. Liudmila Nickelson	723
	Table of Main Designations	725
	Bibliography	733
	Index	735

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 $f \sim 0.3\text{--}430$ 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 (~ 0.79 – 30 PHz)
VG TU	Vilnius Gediminas Technical University
VIS	Visible range (~ 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