

教育部高等教育司推荐
国外优秀信息科学与技术系列教学用书

电磁波理论(上)

影印版

Electromagnetic Wave Theory (1)

■ JIN AU KONG

高等教育出版社
Higher Education Press

EMW Publishing

教育部 高等教育司 推荐
国外优秀信息科学与技术系列教学用书

电磁波理论 (上)

影印版

Electromagnetic Wave Theory (1)

JIN AU KONG

高等教育出版社
Higher Education Press
EMW Publishing

图字: 01-2002-1801 号

Electromagnetic Wave Theory

Jin Au Kong

Copyright© 2000 by Jin Au Kong

English Reprint Copyright© Higher Education Press, 2002

All Rights Reserved.

图书在版编目 (CIP) 数据

电磁波理论. 上 = Electromagnetic Wave Theory/
(美) 孔金瓯 (Kong, J.A.) 著. —北京: 高等教育
出版社, 2002.9

ISBN 7-04-011590-5

I. 电… II. 孔… III. 电磁波 - 理论 - 英文
IV. 0441.4

中国版本图书馆 CIP 数据核字(2002)第 066216 号

电磁波理论(上)影印版

JIN AU KONG

出版发行	高等教育出版社	购书热线	010-64054588
社 址	北京市东城区沙滩后街 55 号	免费咨询	800-810-0598
邮政编码	100009	网 址	http://www.hep.edu.cn
传 真	010-64014048		http://www.hep.com.cn

经 销 新华书店北京发行所
印 刷 北京人卫印刷厂

开 本	787×1092 1/16	版 次	2002 年 9 月第 1 版
印 张	20	印 次	2002 年 9 月第 1 次印刷
字 数	300 000	定 价	21.00 元

本书如有缺页、倒页、脱页等质量问题,请到所购图书销售部门联系调换。

版权所有 侵权必究

前 言

20 世纪末，以计算机和通信技术为代表的信息科学和技术对世界经济、科技、军事、教育和文化等产生了深刻影响。信息科学技术的迅速普及和应用，带动了世界范围信息产业的蓬勃发展，为许多国家带来了丰厚的回报。

进入 21 世纪，尤其随着我国加入 WTO，信息产业的国际竞争将更加激烈。我国信息产业虽然在 20 世纪末取得了迅猛发展，但与发达国家相比，甚至与印度、爱尔兰等国家相比，还有很大差距。国家信息化的发展速度和信息产业的国际竞争能力，最终都将取决于信息科学技术人才的质量和数量。引进国外信息科学和技术优秀教材，在有条件的学校推动开展英语授课或双语教学，是教育部为加快培养大批高质量的信息技术人才采取的一项重要举措。

为此，教育部要求由高等教育出版社首先开展信息科学和技术教材的引进试点工作。同时提出了两点要求，一是要高水平，二是要低价格。在高等教育出版社和信息科学技术引进教材专家组的努力下，经过比较短的时间，第一批引进的 20 多种教材已经陆续出版。这套教材出版后受到了广泛的好评，其中有不少是世界信息科学技术领域著名专家、教授的经典之作和反映信息科学技术最新进展的优秀作品，代表了目前世界信息科学技术教育的一流水平，而且价格也是最优惠的，与国内同类自编教材相当。

这项教材引进工作是在教育部高等教育司和高教社的共同组织下，由国内信息科学技术领域的专家、教授广泛参与，在对大量国外教材进行多次遴选的基础上，参考了国内和国外著名大学相关专业的课程设置进行系统引进的。其中，John Wiley 公司出版的贝尔实验室信息科学研究中心副总裁 Silberschatz 教授的经典著作《操作系统概念》，是我们经过反复谈判，

做了很多努力才得以引进的。William Stallings 先生曾编写了在美国深受欢迎的信息科学技术系列教材，其中有多种教材获得过美国教材和学术著作协会颁发的计算机科学与工程教材奖，这批引进教材中就有他的两本著作。留美中国学者 Jiawei Han 先生的《数据挖掘》是该领域中具有里程碑意义的著作。由达特茅斯学院的 Thomas Cormen 和麻省理工学院、哥伦比亚大学的几位学者共同编著的经典著作《算法导论》，在经历了 11 年的锤炼之后于 2001 年出版了第二版。目前任教于美国 Massachusetts 大学的 James Kurose 教授，曾在美国三所高校先后 10 次获得杰出教师或杰出教学奖，由他主编的《计算机网络》出版后，以其体系新颖、内容先进而倍受欢迎。在努力降低引进教材售价方面，高等教育出版社做了大量和细致的工作。这套引进的教材体现了权威性、系统性、先进性和经济性等特点。

教育部也希望国内和国外的出版商积极参与此项工作，共同促进中国信息技术教育和信息产业的发展。我们在与外商的谈判工作中，不仅要坚定不移地引进国外最优秀的教材，而且还要千方百计地将版权转让费降下来，要让引进教材的价格与国内自编教材相当，让广大教师和学生负担得起。中国的教育市场巨大，外国出版公司和国内出版社要通过扩大发行数量取得效益。

在引进教材的同时，我们还应做好消化吸收，注意学习国外先进的教学思想和教学方法，提高自编教材的水平，使我们的教学和教材在内容体系上，在理论与实践的结合上，在培养学生的动手能力上能有较大的突破和创新。

目前，教育部正在全国 35 所高校推动示范性软件学院的建设和实施，这也是加快培养信息科学技术人才的重要举措之一。示范性软件学院要立足于培养具有国际竞争力的实用性软件人才，与国外知名高校或著名企业合作办学，以国内外著名 IT 企业为实践教学基地，聘请国内外知名教授和软件专家授课，还要率先使用引进教材开展教学。

我们希望通过这些举措，能在较短的时间，为我国培养一大批高质量的信息技术人才，提高我国软件人才的国际竞争力，促进我国信息产业的

快速发展，加快推动国家信息化进程，进而带动整个国民经济的跨越式发展。

教育部高等教育司

二〇〇二年三月

PREFACE

This book presents a unified macroscopic theory of electromagnetic waves in accordance with the principle of special relativity from the point of view of the form invariance of the Maxwell equations and the constitutive relations. Great emphasis is placed on the fundamental importance of the $\vec{k}$ vector in electromagnetic wave theory. We introduce a fundamental unit $K_o = 2\pi \text{ meter}^{-1}$ for the spatial frequency, which is cycle per meter in spatial variation. This is similar to the fundamental unit for temporal frequency Hz, which is cycle per second in time variation. The unit K_o is directly proportional to the unit Hz; one K_o in spatial frequency corresponds to 300 MHz in temporal frequency.

This is a textbook on electromagnetic wave theory, and topics essential to the understanding of electromagnetic waves are selected and presented. Chapter 1 presents fundamental laws and equations for electromagnetic theory. Chapter 2 is devoted to the treatment of transmission line theory. Time-harmonic fields are introduced in Chapter 3 to study propagation, reflection, transmission, guidance, and resonance of electromagnetic waves. Starting with Čerenkov radiation, we study radiation and antenna theory in Chapter 4. Chapter 5 then elaborates on the various theorems and limiting cases of Maxwell's theory important to the study of electromagnetic wave behavior. Scattering by spheres, cylinders, rough surfaces, and volume inhomogeneities are treated in Chapter 6. In Chapter 7, we present Maxwell's theory from the point of view of Lorentz covariance in accordance with the principle of special relativity.

The problem section at the end of each section provides useful exercise and applications. The various topics in the book can be taught independently, and the material is organized in the order of increasing complexity in mathematical techniques and conceptual abstraction and sophistication. This book has been used in several undergraduate and graduate courses that I have been teaching at the Massachusetts Institute of Technology. The undergraduate course covers Chapters 1 and 2 without topic 1.2A and Sections 1.3B, 1.8 and 1.9. The introductory graduate course covers Chapters 1, 3, 4 and parts of Chapter 5. The rest of the book is used for advanced graduate courses.

The first version of the book was published in 1975 by Wiley Interscience, New York, entitled *Theory of Electromagnetic Waves*, which was based on my 1968 Ph.D. thesis, where the concept of bianisotropic media was introduced. The book was expanded and published in 1986 with the present title and its second edition appeared in 1990. Since 1998, it has been published by EMW Publishing Company, Massachusetts. The development of the various concepts in the book relies heavily on published work. I have not attempted the task of referring to all relevant publications. The list of books and journal articles in the Reference Section at the end of the book is at best representative and by no means exhaustive. Some of the results contained in the book are taken from many of my research projects, which have been supported by grants and contracts from the National Science Foundation, the National Aeronautics and Space Administration, the Office of Naval Research, the Army Research Office, the Jet Propulsion Laboratory of the California Institute of Technology, the MIT Lincoln Laboratory, the Schlumberger-Doll Research Center, the Digital Equipment Corporation, and the IBM Corporation. I am particularly grateful to the funding support associated with the award of the S. T. Li prize for the year 2000.

During the writing and preparation of the book, many people helped. In particular, I would like to acknowledge Bae-Ian Wu, who prepared the current version and provided solutions and figures for many of the problems. Chi On Ao formulated the $\text{\TeX}$ macros, meticulously edited the text, and constructed the index. Over the years, many of my teaching and research assistants provided useful suggestions and proofreading, notably Leung Tsang, Michael Zuniga, Weng Chew, Tarek Habashy, Robert Shin, Shun-Lien Chuang, Jay Kyoon Lee, Apo Sezginer, Soon Yun Poh, Eric Yang, Michael Tsuk, Hsiu Chi Han, Yan Zhang, and Henning Braunisch. I would like to express my gratitude to them and to the students whose enthusiastic response and feedback continuously give me joy and satisfaction in teaching.

J. A. Kong

Cambridge, Massachusetts
April 2000

责任编辑 李 慧
封面设计 张 楠
责任印制 宋克学

郑 重 声 明

高等教育出版社依法对本书享有专有出版权。任何未经许可的复制、销售行为均违反《中华人民共和国著作权法》。行为人将承担相应的民事责任和行政责任,构成犯罪的,将被依法追究刑事责任。社会各界人士如发现上述侵权行为,希望及时举报,本社将奖励举报有功人员。

现公布举报电话及通讯地址:

电 话:(010) 84043279 13801081108

传 真:(010) 64033424

E-mail:dd@hep.com.cn

地 址:北京市东城区沙滩后街 55 号

邮 编:100009

CONTENTS

Chapter 1.	FUNDAMENTALS	1
1.1	Maxwell Equations in Free Space	3
	A. Spatial Frequency k	8
	B. Vector Analysis and Boundary Conditions	13
1.2	Polarization	39
	Topic 1.2A Stokes Parameters and Poincaré Sphere	44
1.3	Lorentz Force Law	54
	A. Poynting's Theorem and Poynting's Vector	60
	B. Momentum Conservation Theorem	63
1.4	Hertzian Waves	67
	Topic 1.4A Electric Field Pattern	75
1.5	Waves in Media	84
	A. Wave Vector $\bar{k}$	84
	B. Waves in Conducting Media	87
	C. Waves in Plasma Media	90
	D. Waves in Uniaxial Media	95
1.6	Wave Reflections	101
1.7	Wave Guidance	122
	A. Guidance by Conducting Parallel Plates	122
	B. Guidance by Rectangular Waveguides	129
	C. Rectangular Cavity Resonators	134
1.8	Constitutive Relations	144
	A. Anisotropic and Bianisotropic Media	146
	Topic 1.8A Constitutive Matrices	149
1.9	Boundary Conditions	155
	Topic 1.9A Derivation of Boundary Conditions	155
	Topic 1.9B Boundary Conditions for Moving Boundaries	157
	Answers	162

Chapter 2.	TRANSMISSION LINES	179
2.1	Transmission Line Theory	180
	A. Wave Equations and Wave Solutions	183
	B. Poynting's Theorem	185
	Topic 2.1A Circuit Theory	186
2.2	Transients on Transmission Lines	191
2.3	Sinusoidal Steady State Transmission Lines	206
	A. Reflection from a Terminated Transmission Line	209
	B. Input Impedance	210
	C. Generalized Reflection Coefficient	212
	Topic 2.3A Smith Chart	215
2.4	Lumped Element Transmission Lines	224
2.5	Normal modes on Transmission Lines	245
	A. Normal Modes and Natural Frequencies	245
	B. Initial Value Problem	247
2.6	Transmission Line Modeling	261
	A. Modeling Reflection and Transmission	261
	B. Modeling Antenna Radiation	266
	Topic 2.6A Pattern Multiplication Technique	275
	C. Modeling Radiation by Current Sheets	279
	Topic 2.6B Equivalence Principle	280
	Answers	296
Chapter 3.	PROPAGATION AND GUIDANCE	303
3.1	Time-Harmonic Fields	305
	A. Maxwell Equations for Time-Harmonic Fields	305
	B. Constitutive Relations and Dispersive Media	306
	C. Time-Average Poynting Power Vector	311
	Topic 3.1A Symmetry Conditions for Lossless Media	314
3.2	Plane Wave Solutions	319
	A. Phase and Group Velocities	321

	B. Penetration Depth in Lossy Media	324
	C. Evanescent Waves in Lossless Media	325
3.3	Waves in Media and the kDB System	331
	A. kDB System	331
	B. Maxwell Equations in kDB System	335
	C. Plane Waves in Uniaxial Media	338
	Topic 3.3A Plane Waves in Gyrotropic Media	345
	Topic 3.3B Plane Waves in Bianisotropic Media	350
	Topic 3.3C Plane Waves in Nonlinear Media	353
3.4	Reflection and Transmission	370
	A. Phase Matching	370
	B. Reflection and Transmission at a Plane Boundary	376
	C. Reflection and Transmission by a Layered Medium	385
3.5	Guidance	407
	A. Guidance by Conducting Parallel Plates	407
	B. Guided Waves in a Slab Dielectric Waveguide	424
	C. Guided Waves in Layered Media	429
	D. Cylindrical Rectangular Waveguides	439
	E. Cylindrical Circular Waveguides	444
3.6	Resonance	466
	A. Rectangular Cavity Resonator	466
	B. Circular Cavity Resonator	469
	C. Spherical Cavity Resonator	471
	Topic 3.6A Cavity Perturbation	474
	Answers	481
Chapter 4.	RADIATION	497
4.1	Čerenkov Radiation	499
4.2	Green's Functions	505
	A. Dyadic Green's Functions	505

	B. Radiation Field Approximation	509
4.3	Hertzian Dipoles	515
	A. Hertzian Electric Dipole	515
	B. Hertzian Magnetic Dipole and Small Loop Antenna	520
4.4	Linear Dipole Arrays	526
	A. Uniform Array Antenna with Progressive Phase Shift	526
	B. Array Antennas with Nonuniform Current Distributions	533
	C. Dolph-Chebyshev Arrays	536
	D. Array Pattern Synthesis	542
4.5	Linear Antennas	555
4.6	Biconical Antennas	564
	A. Formulation and Wave Solutions	564
	B. Solution in the Air Region and Dipole Fields	568
	C. Solution in the Antenna Region	570
	D. Transmission Line Model	572
	E. Formal Solution of the Biconical Antenna Problem	578
4.7	Dipole Antennas in Layered Media	582
	A. Integral Formulation	582
	B. Contour Integration Methods	591
	Topic 4.7A Dipole on a Two-Layer Medium	612
	Answers	640
Chapter 5.	THEOREMS OF WAVES AND MEDIA	649
5.1	Equivalence Principle	651
	A. Electric and Magnetic Dipole Sources	651
	B. Image Sources	652
	C. Electric and Magnetic Current Sheets	653
	D. Impressed and Induced Current Sheets	655

	Topic 5.1A Uniqueness Theorem	663
	Topic 5.1B Duality and Complementarity	664
	Topic 5.1C Mathematical Formulations of Huygens' Principle	672
	Topic 5.1D Fresnel and Fraunhofer Diffraction	682
5.2	Reaction and Reciprocity	702
	A. Reaction	702
	B. Reciprocity	703
	C. Reciprocity Conditions	707
	D. Modified Reciprocity Theorem	709
	Topic 5.2A Stationary Formulas and Rayleigh-Ritz Procedure	710
	Topic 5.2B Method of Moments	718
5.3	Quasi-Static Limits	723
5.4	Geometrical Optics Limit	729
5.5	Paraxial Limit	750
	Topic 5.5A Gaussian Beam	750
5.6	Quantization of Electromagnetic Waves	758
	A. Uncertainty Principle	758
	B. Annihilation and Creation Operators	761
	C. Wave Quantization in Bianisotropic Media	769
	Answers	776
Chapter 6.	.SCATTERING	781
6.1	Scattering by Spheres	783
	A. Rayleigh Scattering	783
	B. Mie Scattering	786
6.2	Scattering by a Conducting Cylinder	792
	A. Exact Solution	792
	B. Watson Transformation	794
	C. Creeping Waves	796

6.3	Scattering by Periodic Rough Surfaces	803
	A. Scattering by Periodic Corrugated Conducting Surfaces	803
	B. Scattering by Periodic Dielectric Surfaces	807
6.4	Scattering by Random Rough Surfaces	816
	A. Kirchhoff Approximation	818
	B. Geometrical Optics Solution	826
	C. Small Perturbation Method	829
6.5	Scattering by Periodic Media	339
	A. First-Order Coupled-Mode Equations	841
	B. Reflection and Transmission by Periodically-Modulated Slab	843
	C. Far-Field Diffraction of a Gaussian Beam	847
6.6	Scattering by Random Media	849
	A. Dyadic Green's Function for Layered Media	850
	B. Scattering by a Half-Space Random Medium	856
6.7	Effective Permittivity for a Volume Scattering Medium	860
	A. Random Discrete Scatterers	862
	B. Effective Permittivity for a Continuous Random Medium	867
	Answers	878
Chapter 7.	ELECTROMAGNETIC WAVE THEORY AND SPECIAL RELATIVITY	883
7.1	Maxwell-Minkowski Theory	885
	Topic 7.1A Amperian Formulation	886
	Topic 7.1B Boffi Formulation	887
	Topic 7.1C Chu Formulation	887
7.2	Lorentz Transformation	889
	Topic 7.2A Derivation of Electromagnetic Field Transformation	893

	Topic 7.2B Lorentz Invariants	898
	Topic 7.2C Electromagnetic Field Classification	900
	Topic 7.2D Transformation of Frequency and Wave Vector	902
	Topic 7.2E Aberration Effect	903
	Topic 7.2F Doppler Effect	904
7.3	Waves in Moving Media	913
	A. Transformation of Constitutive Relations	913
	Topic 7.3A Plane Waves in Moving Uniaxial Media	918
	Topic 7.3B Phase Matching at Moving Boundaries	923
	Topic 7.3C Force on a Moving Dielectric Half-space	925
	Topic 7.3D Guided Waves in a Moving Dielectric Slab	928
	Topic 7.3E Guided Waves in Moving Gyrotropic Media	931
7.4	Maxwell Equations in Tensor Form	936
	Topic 7.4A Contravariant and Covariant Vectors	938
	Topic 7.4B Field Tensor and Excitation Tensor	944
	Topic 7.4C Constitutive Relations in Tensor Form	946
7.5	Hamilton's Principle and Noether's Theorem	948
	A. Action Integral	948
	B. Hamilton's Principle and Maxwell Equations	948
	C. Noether's Theorem and Energy Momentum Tensors	950
	Answers	955
	REFERENCES	959
	INDEX	981