QUANTUM ELECTRONICS

Third Edition

Amnon Yariv

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California Institute of Technology

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Preface

The thirteen years that have intervened since the appearance of the second edition of this book have witnessed some important developments in the field of lasers and quantum electronics. Foremost among them are: phase-conjugate optics and its myriad applications, the long wavelength quaternary semiconductor laser, and the deepened understanding of the physics of semiconductor lasers—especially that applying to their current modulation and limiting linewidth, laser arrays and the related concept of supermodes, quantum well semiconductor lasers, the role of phase amplitude coupling in laser noise, and free-electron lasers. The present edition retains nearly all the material of the second edition. There are four new chapters on semiconductor lasers, quantum well lasers, free-electron lasers, and phase-conjugate optics. In addition, the chapters on laser noise and third-order nonlinear effects have been extensively revised.

I benefited from teaching the material and from feedback at Caltech by colleagues and students who aided me in tightening and improving numerous points throughout the book. To these individuals special thanks are due. I am grateful to my administrative assistant, Jana Mercado, for her assistance in preparing this edition. I also take pleasure in thanking the talented group of students and ex-students, especially K. Lau, K. Vahala, C. Harder, T. Koch, M. Cronin-Golomb, S. Kwong, and the late C. Lindsey, whose research efforts are responsible for much of the new material added to this edition. The material on quantum well lasers benefited greatly from my association with Y. Arakawa while David Crouch contributed a major part of the treatment of squeezed states.

Pasadena, California
September 1987

Amnon Yariv

Preface to the Second Edition

This textbook introduces the main principles involved in the study and practice of quantum electronics, which include the theory of laser oscillators, a wide range of optical phenomena, and devices that owe their existence to the intense and coherent optical fields made possible by the laser.

The emphasis is almost exclusively on fundamental principles. An attempt is made, however, to bridge the gap between theory and practice through the use of numerical examples based on real situations.

Approximately one-half of this edition is new. In addition, a number of topics related to microwave phenomena and magnetic resonance were omitted. The major changes are as follows.

1. The addition of treatments on Gaussian beam propagation in lenslike media, optical resonators, density matrix formulation of the interaction of light and matter, theory of laser oscillation, Van der Pol noise analysis of lasers, dye lasers, amplification in vibrational-rotational transitions, double heterojunction lasers, mode locking in homogeneously broadened lasers, Q-switching, saturated amplifiers and amplification of spontaneous emission, acoustooptic interactions, self-induced transparency, photon echoes, spontaneous parametric fluorescence, distributed feedback lasers, and mode coupling in dielectric waveguides.
2. The deletion of chapters dealing with microwave masers, magnetism, magnetic resonance, and microwave parametric oscillators.
3. An exclusive use of the meter-kilogram-second (MKS) unit system.

This text is primarily for the graduate student in physics and applied physics. The latter category often includes students in departments of electrical engineering and material science.

The typical Caltech student taking the course from which this book was developed has a background of a one-year rigorous course in quantum mechanics and one course in electromagnetic theory. These are courses taken by the more advanced students in their senior year but often in the first year of graduate school. A good familiarity with these two topics is assumed, although most of the prerequisite background material is included here.

The book can be used as a basis for a one-year course in quantum electronics or, alternatively, for these one-semester courses:

1. Lasers: Chapters 5–13.
2. Nonlinear Optical Effects and Stimulated Scattering Phenomena: Chapters 14 (part dealing with acoustooptics), 15–18.
3. Optical Modes and Propagation Phenomena: Chapters 5–7, 14, 19.

Course 1 makes heavy use of quantum mechanics. In course 2 quantum mechanics is needed only in Chapter 15, while in course 3 it is not used at all. An electromagnetic background is needed in all three courses.

I apologize to any of my colleagues whose work has not been acknowledged or adequately represented in this book. Since this is primarily a textbook, the material was chosen mainly because of pedagogic considerations rather than chronological precedence.

I thank Ruth Stratton and Dian Rapchak for typing and proofreading the original manuscript and Paula Samazan for assisting with the references.

Thanks are due to Dr. Jack Comly who made important contributions to Chapters 15 and 18 and to Mr. H. W. Yen who has gone over the whole manuscript rederiving the results and checking the internal consistency of the text.

Amnon Yariv

About the Author

Amnon Yariv, a native of Israel, received his higher education at the University of California at Berkeley. After four years at the Bell Telephone Laboratories, he joined the California Institute of Technology (Caltech) where he is the Thomas G. Myers Professor of Electrical Engineering and Applied Physics. At Caltech he studies with a team of doctoral students and postdoctoral fellows, a number of research topics in laser physics, nonlinear optics, and optoelectronics. Some of his major contributions include the invention and co-invention of the fields of integrated optoelectronic circuits, phase conjugate optics, and the authoring of the first papers on the theory of mode locking and nonlinear quantum optics. Dr. Yariv is also the founder and chairman of the board of ORTEL Corporation, a semiconductor laser company in Alhambra, California.

When not working, which is rare, he spends time with his family (wife—Fran and three daughters) as well as with a piano, a tennis racket, and a windsurfer.

Contents

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 11

CHAPTER 12

CHAPTER 13

CHAPTER 14

CHAPTER 21

CHAPTER 22

APPENDIX 1

APPENDIX 2

APPENDIX 3

APPENDIX 4

CHAPTER 1

Basic Theorems and Postulates of Quantum Mechanics

1.0 INTRODUCTION

In this chapter we shall consider some of the basic postulates and theorems of quantum mechanics. These are general and independent of the specific system studied. The application of these results to special problems will be the concern of Chapter 2 and, to a lesser extent, of the rest of the book.

1.1 THE SCHRÖDINGER WAVE EQUATION

According to quantum mechanics, the behavior of a particle is described by the wavefunction $\psi(\mathbf{r}, t)$, which is a solution of the Schrödinger wave equation

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r}, t)\right]\psi = i\hbar\frac{\partial\psi}{\partial t} \tag{1.1-1}$$

$V(\mathbf{r}, t)$ is the potential energy function of the particle and $\hbar = h/2\pi$ where h is Planck's universal constant.

By associating the differential operator $-i\hbar\nabla$ with particle linear momentum $\mathbf{p}$, that is,

$$\mathbf{p} \rightarrow -i\hbar\nabla \tag{1.1-2}$$

the operator on the left side of (1.1-1) can be associated with the sum of the kinetic and potential energy of the particle.

$$E \rightarrow -\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r}, t) = i\hbar\frac{\partial}{\partial t} \tag{1.1-3}$$

Statistical Interpretation of the Wavefunction

Consider a very large number of independent spaces with identical potential functions $V(\mathbf{r}, t)$. The motion of a particle in each one of these spaces is described by the same $\psi(\mathbf{r}, t)$. The a-priori probability $P(\mathbf{r}, t)\,dv$ of finding any given particle inside a volume dv (centered about $\mathbf{r}$) is taken as the fraction of the particles found, by measurement, to be inside dv at time t. According to quantum mechanics, the probability density $P(\mathbf{r}, t)$ is given by

$$P(\mathbf{r}, t) = \psi^*(\mathbf{r}, t)\psi(\mathbf{r}, t) \tag{1.1-4}$$

where the asterisk superscript stands for the complex conjugate of the quantity in question.

The statistical interpretation of $(\psi^*\psi)$ is made plausible by showing, as will be done in Section 1.2, that the average motion of a particle as determined from the statistical point of view agrees with its classical counterpart. The final arbiter of the validity of this statement is, of course, the agreement of the results derived using it with experiment.

The first condition resulting from the statistical interpretation is that the total probability of finding the particle somewhere in space is finite and is a constant, that is,

$$\int_{\text{all space}} P(\mathbf{r}, t)\, dv = \int_{\text{all space}} \psi^*(\mathbf{r}, t)\psi(\mathbf{r}, t)\, dv = \text{constant} \tag{1.1-5}$$

or that

$$\frac{d}{dt}\int_{\text{all space}} \psi^*(\mathbf{r}, t)\psi(\mathbf{r}, t)\, dv = 0 \tag{1.1-6}$$

The proof proceeds as follows

$$\frac{d}{dt}\int_V \psi^*\psi\, dv = \int_V \frac{\partial}{\partial t}(\psi^*\psi)\, dv = \int_V \left(\psi\frac{\partial\psi^*}{\partial t} + \frac{\partial\psi}{\partial t}\psi^*\right) dv$$

substituting for $\partial\psi/\partial t$ and $\partial\psi^*/\partial t$ from (1.1-1), the terms involving $V(\mathbf{r}, t)$ drop out, and the result is

$$\frac{i\hbar}{2m}\int_V (\psi^*\, \nabla^2\psi - \psi\, \nabla^2\psi^*)\, dv$$

Use is now made of Green's theorem

$$\int_V (f\,\nabla^2 g - g\,\nabla^2 f)\, dv = \int_A (f\,\nabla g - g\,\nabla f)\cdot \mathbf{n}\, da \tag{1.1-7}$$

where f and g are two arbitrary scalar functions, A is the surface bounding V, and $\mathbf{n}$ is the unit outward normal vector. This leads to

$$\frac{d}{dt}\int_V (\psi^*\psi)\, dv = \frac{i\hbar}{2m}\int_A (\psi^*\,\nabla\psi - \psi\,\nabla\psi^*)\cdot \mathbf{n}\, da \tag{1.1-8}$$

If the volume V is that of all space, the admissible solutions of (1.1-1) are indeed those in which the behavior of ψ as $r \to \infty$ is such that the integration specified by (1.1-8) leads to a zero result. If the volume V is finite, the same result is obtained by choosing ψ so that its value on the bounding surface A leads to a zero result in (1.1-8). This point is discussed further in Problem 1.1.

Having proven (1.1-5), we are free to normalize ψ so that the constant appearing in (1.1-5) is unity. This is consistent with the probabilistic interpretation, since the probability of finding the particle somewhere in all of space is unity, that is,

$$\int_{V=\text{all space}} P(\mathbf{r}, t)\, dv = \int_V \psi^*(\mathbf{r}, t)\psi(\mathbf{r}, t)\, dv = 1 \tag{1.1-9}$$