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Karl F. Renk

Basics of Laser Physics

For Students of Science and Engineering

With 333 Figures

Springer

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To Marianne, Christiane, and Peter

Preface

This textbook addresses students of science and engineering. It should be appropriate for a senior level applied physics or engineering course on lasers.

There are many textbooks on lasers. Why may it be useful to have another one? I have tried to unify the description of different types of lasers: gas lasers; solid state lasers, including semiconductor lasers; dye lasers; and free-electron lasers. Semiconductor lasers are described in more detail than in other textbooks on lasers. This may be adequate according to the very different types of semiconductor lasers and the many different applications.

What is the working principle of a laser and how is it realizable in different types of lasers? I introduce a laser as an oscillator (= laser oscillator) that generates coherent radiation via the interaction of radiation with an active medium. An active medium consists of an ensemble of atomic systems with a population inversion.

I make use, on an elementary quantum mechanical basis, of the Einstein coefficients of absorption, spontaneous and stimulated emission of radiation to characterize the interaction of radiation with an atomic system. Einstein coefficients are determinable from quantities that are experimentally accessible. I formulate the working principle of a laser by the use of rate equations, yielding the condition of laser oscillation and other properties of a laser.

The main topics of the book concern: the working principle of a laser; the parts of a laser — like the laser resonator and the active medium; beams of radiation generated by a laser; femtosecond laser pulses; and different types of lasers. Additional topics deepen the understanding of more specific questions concerning, in particular: origin of gain in a titanium–sapphire laser; optical frequency analyzer; theory of gain of radiation in doped glass fibers.

It seems that an important type of laser — the free-electron laser — does not meet the criteria of a laser: classical physics is well suited to analyze operation a free-electron laser. I will, nevertheless, illustrate operation of a free-electron laser by use of an energy-level description. An active medium of a free-electron laser consists of oscillating free electrons. I attribute, to an oscillating free electron, an energy-ladder system. In this description, population inversion occurs in an ensemble of energy-ladder systems; the concept is known for a particular semiconductor laser — the superlattice Bloch laser (also called Bloch oscillator) — that exists, however, only as an idea based on theoretical work. The energy-level description illustrates similarities of free-electron lasers and conventional lasers as well as differences between them.

A chapter comparing laser oscillators and quasiclassical solid state oscillators provides a connection to textbooks covering the field of microwave oscillators; additionally, the van der Pol oscillator is introduced as a model of a classical oscillator. In contrast to a laser, with a population inversion in an ensemble of quantum systems, a quasiclassical oscillator operates without population inversion: radiation in an active medium interacts with collectives of electrons — the interaction is determined by classical physics but the ability to form appropriate collectives of electrons is of quantum mechanical nature.

A reader may skip, in a first study, several chapters or sections that serve for deepening: Chap. 9 (dynamics of the active medium); Sect. 11.7 (Gouy phase); Sects. 12.9, 12.10, 13.3–13.9 (laser applications); Chap. 17 (physical basis of broadband solid state lasers); Chap. 18 (theory of fiber lasers and amplifiers); Sects. 19.5–19.12 (energy-level description of the free-electron laser); Chap. 21 (theory of semiconductor lasers); Sects. 25.8–25.15 (theory of electromagnetic waves in layered materials); Chap. 26 (discussing quantum well lasers in detail); Chap. 30 (theory of electron waves in semiconductor heterostructures); Chap. 31 (comparing lasers with quasiclassical oscillators); Chap. 32 (Bloch laser); Chaps. 33–35 (laser-related topics). Deepening of topics related to solid state physics (including semiconductor physics) corresponds to my experience in research in solid state spectroscopy. Several other textbooks deepen the discussion of lasers more toward atomic physics or quantum mechanics.

Text illustrations, examples, and exercises should allow a student to follow the main line but also single arguments.

I would like to thank the students who attended my "Laser Physics" course for asking questions about a first manuscript. I thank Alfons Penzkofer for examining a large portion of the manuscript and suggesting many improvements. I am indebted to Al Sievers for very helpful advice with respect to manuscript and exercises. I appreciate many valuable comments from Laurence Eaves, Max Maier, Peter Renk, Jens Siewert, Benjamin Stahl, Herbert Welling, and Ernst Werner. I thank Rupert Huber, Joachim Keller, Tobias Korn, John Lupton, Christoph Strunk, Werner Wegscheider for discussions, and Peter Olbrich for advice on electronic data processing. Ulla Turba has drawn a large part of the figures and has written a large part of the manuscript. I am very grateful for her engagement during preparation of various versions of the manuscript and for allowing me to permanently change text, formula, and drawings. I am indebted to Claus Ascheron for his encouragement to write a book.

Regensburg, Germany *Karl F. Renk*
September 2011

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