

Marlan O. Scully, M. Suhail Zubairy

Quantum Optics

量子光学

CAMBRIDGE

  世界图书出版公司

Quantum optics

Marlan O. Scully

Texas A&M University and Max-Planck-Institut für Quantenoptik

M. Suhail Zubairy

Quaid-i-Azam University



CAMBRIDGE
UNIVERSITY PRESS

图书在版编目 (CIP) 数据

量子光学 = Quantum Optics: 英文 / (美) M. O. 斯库利, (美) M. S. 朱伯瑞著. —影印本. —北京: 世界图书出版有限公司北京分公司, 2018.9
ISBN 978-7-5192-5034-8

I. ①量… II. ①M… ②M… III. ①量子光学—研究生—教材—英文 IV. ①O431.2

中国版本图书馆 CIP 数据核字 (2018) 第 186410 号

中文书名 量子光学
英文书名 Quantum Optics
著 者 Marlan O. Scully, M. Suhail Zubairy
责任编辑 刘 慧 高 蓉
装帧设计 刘敬利

出版发行 世界图书出版有限公司北京分公司
地 址 北京市东城区朝内大街 137 号
邮 编 100010
电 话 010-64038355 (发行) 64033507 (总编室)
网 址 <http://www.wpcbj.com.cn>
邮 箱 wpcbjst@vip.163.com
销 售 新华书店
印 刷 北京建宏印刷有限公司
开 本 710 mm × 1000 mm 1/16
印 张 41
字 数 782 千字
版 次 2018 年 9 月第 1 版
印 次 2018 年 9 月第 1 次印刷
版权登记 01-2018-4663
国际书号 ISBN 978-7-5192-5034-8
定 价 129.00 元

版权所有 翻印必究

(如发现印装质量问题, 请与所购图书销售部门联系调换)

Quantum Optics (978-0-521-43595-6) by M. O. Scully, M. S. Zubairy first published by Cambridge University Press 1997

All rights reserved.

This reprint edition for the People's Republic of China is published by arrangement with the Press Syndicate of the University of Cambridge, Cambridge, United Kingdom.

© Cambridge University Press & Beijing World Publishing Corporation 2018

This book is in copyright. No reproduction of any part may take place without the written permission of Cambridge University Press or Beijing World Publishing Corporation.

This edition is for sale in the mainland of China only, excluding Hong Kong SAR, Macao SAR and Taiwan, and may not be bought for export therefrom.

此版本仅限中华人民共和国境内销售，不包括香港、澳门特别行政区及中国台湾。不得出口。

The field of quantum optics has witnessed significant developments in recent years, from the laboratory realization of counter-intuitive concepts such as lasing without inversion and micromasers, to the investigation of fundamental issues in quantum mechanics, such as complementarity and hidden variables. This book provides an in-depth and wide-ranging introduction to the subject of quantum optics, emphasizing throughout the basic principles and their applications.

The book begins by developing the basic tools of quantum optics, and goes on to show the application of these tools in a variety of quantum optical systems, including resonance fluorescence, lasers, micromasers, squeezed states, and atom optics. The final four chapters are devoted to a discussion of quantum optical tests of the foundations of quantum mechanics, and particular aspects of measurement theory.

Assuming only a background of standard quantum mechanics and electromagnetic theory, and containing many problems and references, this book will be invaluable to graduate students of quantum optics, as well as to established researchers in this field.

Quantum optics

Marlan O. Scully has received numerous honors as a result of his many pioneering contributions as a researcher and educator on both sides of the Atlantic. These include: the Adolph Lomb Medal of the Optical Society of America, the Elliot Cresson Medal of the Franklin Society, Guggenheim Fellowship, and the Alexander von Humboldt Award. He is an elected member of the Max-Planck Society and a Fellow of the American Physical Society, the Optical Society of America, and the American Association of the Advancement of Science. He has held the faculty positions at Yale, MIT, University of Arizona, University of New Mexico and is currently Burgess Distinguished Professor of Physics, Director of the Center for Theoretical Physics at Texas A&M University, Co-Director of the Texas Laser Lab., and Auswärtiges Wissenschaftliches Mitglied at the Max-Planck Institut für Quantenoptik.

M. Suhail Zubairy received his PhD degree from the University of Rochester in 1978. He held research and faculty positions at the University of Rochester, University of Arizona, and the University of New Mexico before joining the Quaid-i-Azam University, Islamabad in 1984 where he is presently a Professor and founding Chairman of the Department of Electronics. He has held visiting appointments at the Max-Planck Institut für Quantenoptik, Universität Ulm, University of New Mexico, and the University of Campinas. He has been an Associate Member of the International Centre for Theoretical Physics, Trieste. He was awarded the Order of Sitara-e-Imtiaz by the President of Pakistan in 1993. He has received the Salam Prize for Physics and a Gold Medal from the Pakistan Academy of Sciences. He is a Fellow of the Pakistan Academy of Sciences and the Optical Society of America.

To

Thelma T. Scully and Naseem Fatima Zubairy

and to the memory of

Orvil O. Scully and Muhibul Islam Zubairy

Preface

Quantum optics, the union of quantum field theory and physical optics, is undergoing a time of revolutionary change. The subject has evolved from early studies on the coherence properties of radiation like, for example, quantum statistical theories of the laser in the sixties to modern areas of study involving, for example, the role of squeezed states of the radiation field and atomic coherence in quenching quantum noise in interferometry and optical amplifiers. On the one hand, counter intuitive concepts such as lasing without inversion and single atom (micro) masers and lasers are now laboratory realities. Many of these techniques hold promise for new devices whose sensitivity goes well beyond the standard quantum limits. On the other hand, quantum optics provides a powerful new probe for addressing fundamental issues of quantum mechanics such as complementarity, hidden variables, and other aspects central to the foundations of quantum physics and philosophy.

The intent of this book is to present these and many other exciting developments in the field of quantum optics to students and scientists, with an emphasis on fundamental concepts and their applications, so as to enable the students to perform independent research in this field. The book (which has developed from our lectures on the subject at various universities, research institutes, and summer schools) may be used as a textbook for beginning graduate students with some background in standard quantum mechanics and electromagnetic theory. Each chapter is supplemented by problems and general references. Some of the problems rely heavily on the treatment given in a research paper, leading students directly to the scientific literature. The role of the references is to identify original papers, and to refer the reader to

review articles and related papers for in-depth study. No attempt is made to give an exhaustive list of references.

The book is divided roughly into three parts. In the first six chapters, we develop the 'tools' of quantum optics. In the next eleven chapters, these 'tools' are applied to various quantum optical systems. In the last four chapters, we consider the application of modern quantum optical physics to testing the foundations of quantum mechanics.

The book opens with the presentation of the quantization of the radiation field by associating each mode of the field with a quantized harmonic oscillator. The strong motivation to quantize the radiation field in many quantum optical systems comes from phenomena such as quantum beats, two-photon interferometry, and the generation of nonclassical states of the radiation field, e.g., Fock states. Some of these phenomena shed new light on our understanding of the elusive concept of the photon. In the first part of the book, we discuss the various states of the radiation field, e.g., coherent and squeezed states, and introduce the distribution functions of the field which form a correspondence between the quantum and the classical theories of radiation. We then develop a quantum theory of coherence in terms of the correlation functions of the field, which provides a framework for discussing the outcome of interferometric experiments. We proceed to develop the semiclassical and quantum theories of the interaction of the radiation field with matter, with an emphasis on formulating a theoretical framework directed toward understanding the many faceted problems of modern quantum optics.

In the second part, we use this theoretical framework to develop theories of atomic and field damping, resonance fluorescence, laser and micromaser operation, and the study of the quantum noise properties of such nonlinear optical processes as parametric amplification and four-wave mixing. Atomic coherence effects in many novel systems are discussed in detail. For example, the role of atomic coherence in suppressing absorption leads to interesting effects such as lasing without inversion and electromagnetically induced transparency. Atomic coherence can also play a role in quenching Schawlow-Townes spontaneous emission noise in lasers, as in the correlated emission laser (CEL). Such CEL systems have potential applications in, e.g., laser gyro physics and 'noise-free' amplification.

In the third part, we move on to the application of modern quantum optical physics to fundamental questions related to the foundation of quantum mechanics. These include Bell's theorem, quantum nondemolition measurements, 'which-path' detectors, and two-photon interferometry.

We have benefited greatly from our interaction with many of our colleagues, friends, and students in the preparation of this book. They are too numerous to be individually acknowledged and we are able to express our gratitude to only a few of them here.

We would especially like to thank Stephen Harris, Willis Lamb, Julian Schwinger, and Herbert Walther, who have strongly influenced our thinking through their profound contributions to physics in general and many fruitful collaborations in particular. Their imprint on this book is evident: but for them, entire chapters would be missing. We are grateful to Peter Knight for providing the encouragement for writing this book. Critical comments from and helpful discussions with him and with Girish Agarwal, Richard Arnowitt, Chris Bednar, Janos Bergou, Leon Cohen, Jonathan Dowling, Joe Eberly, Michael Fleischhauer, Edward Fry, Julio Gea-Banacloche, Roy Glauber, Truong-Dung Ho, Hwang Lee, Lorenzo Narducci, Robert O'Connell, Norman Ramsey, Ulrich Rathe, Wolfgang Schleich, Krzysztof Wodkiewicz, Bernard Yurke, and Shi-Yao Zhu provided invaluable assistance concerning many subtle points. One of us (MSZ) would like to express his gratitude to the Pakistan Atomic Energy Commission for the financial support over the years, and particularly its Chairman, Ishfaq Ahmad, for his deep interest and commitment that played a vital role in the completion of this project. MOS would like to acknowledge the support of the Office of Naval Research, and particularly Herschel Pilloff, whose wisdom and dedication to scientific excellence have resulted in many successful joint projects and conferences which have had a marked impact on this book. The support of the Houston Advanced Research Center (HARC), and the Welch Foundation is also deeply appreciated. We thank Jeanne Williams for the careful typing in $\text{\TeX}$, and Jim and Andrey Bailey for the hospitality of the Bailey ranch, where the manuscript was completed.

Finally, we are grateful to our family members, Judith, James, Debra, Robert, Steven, and Jacquelyn, and Parveen, Sarah, Sahar, and Raheel, for their support, and understanding, especially during the extended absences in the course of the last decade, when this book was contemplated, planned, and written.

Marlan O. Scully
M. Suhail Zubairy

Contents

Preface	xix
1 Quantum theory of radiation	1
1.1 Quantization of the free electromagnetic field	2
1.1.1 Mode expansion of the field	3
1.1.2 Quantization	4
1.1.3 Commutation relations between electric and magnetic field components	7
1.2 Fock or number states	9
1.3 Lamb shift	13
1.4 Quantum beats	16
1.5 What is light? – The photon concept	20
1.5.1 Vacuum fluctuations and the photon concept	20
1.5.2 Vacuum fluctuations	22
1.5.3 Quantum beats, the quantum eraser, Bell's theorem, and more	24
1.5.4 'Wave function for photons'	24
1.A Equivalence between a many-particle Bose gas and a set of quantized harmonic oscillators	35
<i>Problems</i>	40
<i>References and bibliography</i>	43
2 Coherent and squeezed states of the radiation field	46
2.1 Radiation from a classical current	48
2.2 The coherent state as an eigenstate of the annihilation operator and as a displaced harmonic oscillator state	50
2.3 What is so coherent about coherent states?	51
2.4 Some properties of coherent states	54
2.5 Squeezed state physics	56

2.6	Squeezed states and the uncertainty relation	60
2.7	The squeeze operator and the squeezed coherent states	63
2.7.1	Quadrature variance	65
2.8	Multi-mode squeezing	66
	<i>Problems</i>	67
	<i>References and bibliography</i>	70
3	Quantum distribution theory and partially coherent radiation	72
3.1	Coherent state representation	73
3.1.1	Definition of the coherent state representation	75
3.1.2	Examples of the coherent state representation	77
3.2	Q -representation	79
3.3	The Wigner–Weyl distribution	81
3.4	Generalized representation of the density operator and connection between the P -, Q -, and W -distributions	83
3.5	Q -representation for a squeezed coherent state	86
3.A	Verifying equations (3.1.12a, 3.1.12b)	90
3.B	c -number function correspondence for the Wigner–Weyl distribution	92
	<i>Problems</i>	94
	<i>References and bibliography</i>	96
4	Field–field and photon–photon interferometry	97
4.1	The interferometer as a cosmic probe	98
4.1.1	Michelson interferometer and general relativity	98
4.1.2	The Sagnac ring interferometer	101
4.1.3	Proposed ring laser test of metric gravitation theories	106
4.1.4	The Michelson stellar interferometer	108
4.1.5	Hanbury-Brown–Twiss interferometer	110
4.2	Photon detection and quantum coherence functions	111
4.3	First-order coherence and Young-type double-source experiments	115
4.3.1	Young’s double-slit experiment	115
4.3.2	Young’s experiment with light from two atoms	119
4.4	Second-order coherence	120
4.4.1	The physics behind the Hanbury-Brown–Twiss effect	121
4.4.2	Detection and measurement of squeezed states via homodyne detection	125
4.4.3	Interference of two photons	131
4.4.4	Photon antibunching, Poissonian, and sub-Poissonian light	134
4.5	Photon counting and photon statistics	137

4.A	Classical and quantum descriptions of two-source interference	139
4.B	Calculation of the second-order correlation function	140
	<i>Problems</i>	141
	<i>References and bibliography</i>	143
5	Atom-field interaction – semiclassical theory	145
5.1	Atom-field interaction Hamiltonian	146
5.1.1	Local gauge (phase) invariance and minimal-coupling Hamiltonian	146
5.1.2	Dipole approximation and $\mathbf{r} \cdot \mathbf{E}$ Hamiltonian	148
5.1.3	$\mathbf{p} \cdot \mathbf{A}$ Hamiltonian	149
5.2	Interaction of a single two-level atom with a single-mode field	151
5.2.1	Probability amplitude method	151
5.2.2	Interaction picture	155
5.2.3	Beyond the rotating-wave approximation	158
5.3	Density matrix for a two-level atom	160
5.3.1	Equation of motion for the density matrix	161
5.3.2	Two-level atom	162
5.3.3	Inclusion of elastic collisions between atoms	163
5.4	Maxwell-Schrödinger equations	164
5.4.1	Population matrix and its equation of motion	165
5.4.2	Maxwell's equations for slowly varying field functions	166
5.5	Semiclassical laser theory	168
5.5.1	Basic principle	169
5.5.2	Lamb's semiclassical theory	169
5.6	A physical picture of stimulated emission and absorption	173
5.7	Time delay spectroscopy	174
5.A	Equivalence of the $\mathbf{r} \cdot \mathbf{E}$ and the $\mathbf{p} \cdot \mathbf{A}$ interaction Hamiltonians	178
5.A.1	Form-invariant physical quantities	178
5.A.2	Transition probabilities in a two-level atom	180
5.B	Vector model of the density matrix	183
5.C	Quasimode laser physics based on the modes of the universe	185
	<i>Problems</i>	187
	<i>References and bibliography</i>	190
6	Atom-field interaction – quantum theory	193
6.1	Atom-field interaction Hamiltonian	194

6.2	Interaction of a single two-level atom with a single-mode field	196
6.2.1	Probability amplitude method	197
6.2.2	Heisenberg operator method	202
6.2.3	Unitary time-evolution operator method	204
6.3	Weisskopf–Wigner theory of spontaneous emission between two atomic levels	206
6.4	Two-photon cascades	210
6.5	Excitation probabilities for single and double photo-excitation events	213
	<i>Problems</i>	215
	<i>References and bibliography</i>	217
7	Lasing without inversion and other effects of atomic coherence and interference	220
7.1	The Hanle effect	221
7.2	Coherent trapping – dark states	222
7.3	Electromagnetically induced transparency	225
7.4	Lasing without inversion	230
7.4.1	The LWI concept	230
7.4.2	The laser physics approach to LWI: simple treatment	232
7.4.3	LWI analysis	233
7.5	Refractive index enhancement via quantum coherence	236
7.6	Coherent trapping, lasing without inversion, and electromagnetically induced transparency via an exact solution to a simple model	241
	<i>Problems</i>	244
	<i>References and bibliography</i>	245
8	Quantum theory of damping – density operator and wave function approach	248
8.1	General reservoir theory	249
8.2	Atomic decay by thermal and squeezed vacuum reservoirs	250
8.2.1	Thermal reservoir	251
8.2.2	Squeezed vacuum reservoir	253
8.3	Field damping	255
8.4	Fokker–Planck equation	256
8.5	The ‘quantum jump’ approach to damping	260
8.5.1	Conditional density matrices and the null measurement	261
8.5.2	The wave function Monte Carlo approach to damping	263

<i>Problems</i>	267
<i>References and bibliography</i>	269
9 Quantum theory of damping – Heisenberg–Langevin approach	271
9.1 Simple treatment of damping via oscillator reservoir: Markovian white noise	272
9.2 Extended treatment of damping via atom and oscillator reservoirs: non-Markovian colored noise	276
9.2.1 An atomic reservoir approach	276
9.2.2 A generalized treatment of the oscillator reservoir problem	278
9.3 Equations of motion for the field correlation functions	281
9.4 Fluctuation–dissipation theorem and the Einstein relation	283
9.5 Atom in a damped cavity	284
<i>Problems</i>	289
<i>References and bibliography</i>	290
10 Resonance fluorescence	291
10.1 Electric field operator for spontaneous emission from a single atom	292
10.2 An introduction to the resonance fluorescence spectrum	293
10.2.1 Weak driving field limit	293
10.2.2 The strong field limit: sidebands appear	295
10.2.3 The widths of the three peaks in the very strong field limit	296
10.3 Theory of a spectrum analyzer	298
10.4 From single-time to two-time averages: the Onsager– Lax regression theorem	300
10.5 The complete resonance fluorescence spectrum	302
10.5.1 Weak field limit	305
10.5.2 Strong field limit	305
10.6 Photon antibunching	307
10.7 Resonance fluorescence from a driven V system	309
10.A Electric field operator in the far-zone approximation	311
10.B The equations of motion for and exact solution of the density matrix in a dressed-state basis	316
10.B.1 Deriving the equation of motion in the dressed-state basis	316
10.B.2 Solving the equations of motion	317

10.C	The equations of motion for and exact solution of the density matrix in the bare-state basis	320
10.D	Power spectrum in the stationary regime	321
10.E	Derivation of Eq. (10.7.5)	322
	<i>Problems</i>	323
	<i>References and bibliography</i>	325
11	Quantum theory of the laser – density operator approach	327
11.1	Equation of motion for the density matrix	328
11.2	Laser photon statistics	336
11.2.1	Linear approximation ($\mathcal{B} = 0$)	337
11.2.2	Far above threshold ($\mathcal{A} \gg \mathcal{C}$)	338
11.2.3	Exact solution	338
11.3	P -representation of the laser	340
11.4	Natural linewidth	341
11.4.1	Phase diffusion model	342
11.4.2	Fokker–Planck equation and laser linewidth	345
11.5	Off-diagonal elements and laser linewidth	346
11.6	Analogy between the laser threshold and a second-order phase transition	349
11.A	Solution of the equations for the density matrix elements	352
11.B	An exact solution for the P -representation of the laser	354
	<i>Problems</i>	358
	<i>References and bibliography</i>	360
12	Quantum theory of the laser – Heisenberg–Langevin approach	362
12.1	A simple Langevin treatment of the laser linewidth including atomic memory effects	362
12.2	Quantum Langevin equations	367
12.3	c -number Langevin equations	373
12.4	Photon statistics and laser linewidth	376
	<i>Problems</i>	380
	<i>References and bibliography</i>	381
13	Theory of the micromaser	383
13.1	Equation of motion for the field density matrix	384
13.2	Steady-state photon statistics	386
13.3	Preparation of number state in a high- Q micromaser	389
13.3.1	State reduction	390
13.3.2	Trapping states	393
13.4	Linewidth of a micromaser	396