

Nonlinear Optical Systems

Guiding graduate students and researchers through the complex world of laser physics and nonlinear optics, this book provides an in-depth exploration of the dynamics of lasers and other relevant optical systems, under the umbrella of a unitary spatio-temporal vision.

Adopting a balanced approach, the book covers traditional as well as special topics in laser physics, quantum electronics and nonlinear optics, treating them from the viewpoint of nonlinear dynamical systems. These include laser emission, frequency generation, solitons, optically bistable systems, pulsations and chaos and optical pattern formation. It also provides a coherent and up-to-date treatment of the hierarchy of nonlinear optical models and of the rich variety of phenomena they describe, helping readers to understand the limits of validity of each model and the connections among the phenomena. It is ideal for graduate students and researchers in nonlinear optics, quantum electronics, laser physics and photonics.

Luigi Lugiato is a Professor Emeritus at the Università dell'Insubria, Como, Italy. He has received numerous honors as a result of his many pioneering contributions in nonlinear optics and quantum optics. These include the Albert A. Michelson Medal of the Franklin Institute, the Quantum Electronics Prize of the European Physical Society, the Max Born Award of the Optical Society of America and the Fermi Prize and Medal of the Italian Physical Society. He is a member of the Academia Europaea and a Fellow of the Optical Society of America, the American Physical Society and the European Physical Society.

Franco Prati is an Associate Professor at the Università dell'Insubria, Como, Italy. He has worked in laser physics and nonlinear optics since 1987. His main contributions concern the study of temporal and spatio-temporal instabilities in nonlinear optical systems. He is the co-author of more than 80 papers in peer-reviewed journals, and he is an Outstanding Referee of the American Physical Society and a member of the Optical Society of America.

Massimo Brambilla is an Associate Professor at the Politecnico di Bari, Italy. He has worked in nonlinear and quantum optics since 1986, participating in the early studies of optical pattern formation and dynamics and contributing to more than 100 journal papers and numerous conference presentations. He is active in theoretical research on nonlinear optical systems, with a special focus on the spatio-temporal dynamics of coherent field and solitonic phenomena. He is a member of the Optical Society of America.

Cambridge University Press
978-1-107-06267-2 - Nonlinear Optical Systems
Luigi Lugiato, Franco Prati and Massimo Brambilla
Excerpt
[More information](#)

Cambridge University Press
978-1-107-06267-2 - Nonlinear Optical Systems
Luigi Lugiato, Franco Prati and Massimo Brambilla
Excerpt
[More information](#)

Nonlinear Optical Systems

LUIGI LUGIATO

Università degli Studi dell'Insubria, Italy

FRANCO PRATI

Università degli Studi dell'Insubria, Italy

MASSIMO BRAMBILLA

Politecnico di Bari, Italy



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
978-1-107-06267-2 - Nonlinear Optical Systems
Luigi Lugiato, Franco Prati and Massimo Brambilla
Excerpt
[More information](#)

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9781107062672

© L. Lugiato, F. Prati & M. Brambilla 2015

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2015

Printed in the United Kingdom by TJ International Ltd. Padstow Cornwall

A catalog record for this publication is available from the British Library

ISBN 978-1-107-06267-2 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Cambridge University Press
978-1-107-06267-2 - Nonlinear Optical Systems
Luigi Lugiato, Franco Prati and Massimo Brambilla
Excerpt
[More information](#)

To Vilma, Roberta, Monica

Cambridge University Press
978-1-107-06267-2 - Nonlinear Optical Systems
Luigi Lugiato, Franco Prati and Massimo Brambilla
Excerpt
[More information](#)

Contents

<i>Preface</i>	<i>page xiii</i>
Part I Models, propagation, stationary phenomena	1
Introduction to Part I	3
1 The rate-equation model for the laser	5
1.1 Absorption, stimulated emission and spontaneous emission	5
1.2 Calculation of the <i>B</i> coefficient	7
1.3 The laser	9
2 The interaction of a system of two-level atoms with the electromagnetic field	15
2.1 The interaction Hamiltonian in the dipole approximation	15
2.2 The two-level atom and its analogy with spin 1/2	17
2.3 The rotating-wave approximation. Optical Bloch equations	19
2.4 The Bloch vector and its nutation	21
3 The Maxwell–Bloch equations	29
3.1 The Maxwell equations. Paraxial and slowly varying envelope approximations	29
3.2 The Maxwell–Bloch equations. The plane-wave approximation	33
3.3 Self-induced transparency, the sine–Gordon equation and solitons	34
3.4 Superradiance and superfluorescence	37
4 Inclusion of the irreversible processes in the atomic equations	43
4.1 Irreversible transition processes between the two levels	43
4.2 Irreversible decay of the atomic polarization	45
4.3 Damped Rabi oscillations and the approach to a stationary state	47
4.4 The complete Maxwell–Bloch equations	48
5 Propagation in irreversible Maxwell–Bloch equations	49
5.1 Linear theory	49
5.2 Saturation and power broadening	53
5.3 Nonlinear propagation for a monochromatic input field: The role of saturation and nonlinear phase shift	55
5.4 Background linear dispersion and absorption	57

6 Optical nonlinearities. Materials with quadratic nonlinearities	60
6.1 Linear and nonlinear polarization	61
6.2 Media with a quadratic nonlinearity	63
6.3 The stationary state in the plane-wave approximation	67
7 Optical nonlinearities. Materials with cubic nonlinearities	74
7.1 The Kerr medium nonlinearity. Self-phase modulation	74
7.2 Temporal Kerr solitons	76
7.3 Spatial Kerr solitons	78
7.4 The case of three frequency bands. Cross-phase modulation and four-wave mixing	79
7.5 Optical phase conjugation	81
8 Optical resonators. The planar ring cavity. Empty cavity. Linear cavity	85
8.1 Optical cavities	85
8.2 Beam splitters	86
8.3 The planar ring cavity. Boundary condition, input and output fields. Transmission of the cavity	87
8.4 The empty cavity	90
8.5 The linear cavity. Frequency pulling and pushing, mode splitting	92
9 A nonlinear active ring cavity: the ring laser, stationary states	95
9.1 Calculation of the nontrivial stationary solutions	95
9.2 The low-transmission limit	99
9.3 The analogy with second-order phase transitions	101
10 The adiabatic elimination principle	105
10.1 General formulation of the principle	105
10.2 Adiabatic elimination of the atomic polarization in the Bloch equations. Limits of the optical pumping between two levels	107
10.3 The three-level optical-pumping scheme	108
10.4 The four-level optical-pumping scheme	110
11 A nonlinear passive ring cavity: optical bistability	112
11.1 Absorptive optical bistability	112
11.2 Dispersive optical bistability	117
11.3 Optical bistability in two-level systems: the general case	120
11.4 Functionalities of optically bistable systems	123
12 Modal equations for the ring cavity. The single-mode model	126
12.1 Transformation of coordinates and transformation of variables. Modal equations	127
12.2 Introduction of the low-transmission approximation	131
12.3 The single-mode model	132
12.4 Stationary solutions of the single-mode model	134

13 Single- and two-mode models	135
13.1 A laser with an injected signal	135
13.2 A laser with a saturable absorber	139
13.3 The cubic model for dispersive optical bistability	142
13.4 A model for the degenerate optical parametric oscillator (and harmonic generation in a cavity) and its stationary solutions	144
14 Nonlinear dynamics in Fabry–Perot cavities	150
14.1 Modal equations for the Fabry–Perot cavity	151
14.2 The single-mode model for the Fabry–Perot cavity. Spatial hole-burning	156
14.3 A more convenient set of modal equations	159
14.4 Again the ring cavity: simplified forms of the models	163
14.5 The case of an atomic sample of length much shorter than the wavelength: difference-differential equations	165
15 Inhomogeneous broadening	170
15.1 Multimode dynamical equations	170
15.2 The single-mode model. The stationary state for the laser. Spectral hole-burning	172
16 The semiconductor laser	177
16.1 Some elements of semiconductor physics	177
16.2 The p–n junction	179
16.3 The double heterojunction. Optical confinement	180
16.4 Band structure	182
16.5 Dynamical equations	184
16.6 Vertical-cavity surface-emitting lasers	190
17 Lasers without inversion and the effects of atomic coherence	192
17.1 Model equations	192
17.2 Coherent population trapping	194
17.3 Electromagnetically induced transparency	196
17.4 Amplification without inversion	199
17.5 Lasing without inversion	202
Part II Dynamical phenomena, instabilities, chaos	205
Introduction to Part II	207
18 Some general aspects in nonlinear dissipative dynamical systems	209
18.1 Stationary solutions and their stability	210
18.2 Attractors and repellers; bistability and multistability	212
18.3 Other kinds of attractors: limit cycles, tori, strange attractors; deterministic chaos; generalized multistability	213
18.4 Transitions induced by the variation of a control parameter	214

19 Special limits in the single-mode model	219
19.1 Classification of lasers	219
19.2 Adiabatic elimination of the atomic variables (the good-cavity limit)	220
19.3 Adiabatic elimination of the atomic polarization: the single-mode rate-equation model	225
19.4 Adiabatic elimination of the electric field (the bad-cavity limit)	232
20 The linear-stability analysis of the Maxwell–Bloch equations	233
20.1 Coupled multimodal equations for field and atomic variables. Single-mode and multimode instabilities	234
20.2 Multimode instabilities and their features	238
20.3 Single-mode instabilities and their features	241
20.4 The general connection between single-mode and multimode instabilities	244
20.5 The resonant case, amplitude and phase instabilities	244
21 Adiabatic elimination in the complete Maxwell–Bloch equations	247
21.1 The rate-equation approximation	247
21.2 Adiabatic elimination of the atomic polarization and comparison with the rate-equation approximation	248
21.3 Adiabatic elimination of the atomic variables	249
22 Dynamical aspects in the laser	252
22.1 Linear-stability analysis of the trivial stationary solution in the standard laser	252
22.2 Linear-stability analysis of the trivial stationary solution in the laser without inversion	254
22.3 Class-C lasers: the analogy with the Lorenz model and optical chaos	255
22.4 The resonant single-mode laser instability	257
22.5 The multimode amplitude instability	261
22.6 The multimode phase instability	265
22.7 An ultrathin medium: the multimode amplitude instability in the Fabry–Perot laser	269
23 Single-mode and multimode operation in inhomogeneously broadened lasers	275
23.1 Multimode and single-mode instabilities	276
23.2 Mode-locking	285
24 Dynamical aspects in optical bistability	288
24.1 Critical slowing down	288
24.2 Multimode instabilities in optical bistability	291
24.3 Single-mode instabilities in optical bistability	300
25 Self-pulsing in other optical systems	306
25.1 A laser with an injected signal. Frequency locking and coexisting attractors	306