

Edited by

K. Busch, S. Lölkes, R. B. Wehrspohn, and H. Föll

Photonic Crystals

Advances in Design, Fabrication, and Characterization



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*K. Busch, S. Lölkes, R. B. Wehrspohn,
and H. Föll (Eds.)*

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Coverpicture

(Main picture) Simulation of field distribution in a photonic crystal (PhC) waveguide with integrated beam splitter. (Background) SEM picture of an electrochemically etched 3D PhC with a full photonic bandgap in the IR. (Foreground) Emission spectrum of a PhC laser.

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Library of Congress Card No.: applied for British Library Cataloging-in-Publication Data:

A catalogue record for this book is available from the British Library

Bibliographic information published by Die Deutsche Bibliothek

Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data is available in the Internet at <<http://dnb.ddb.de>>.

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Printed in the Federal Republic of Germany
Printed on acid-free paper

Cover Design Petra Beisert, conimago

Composition Uwe Krieg, Berlin

Printing Druckhaus Darmstadt GmbH,
Darmstadt

Bookbinding Großbuchbinderei J. Schäffer
GmbH & Co. KG, Grünstadt

ISBN 3-527-40432-5

Contents

Preface	XIII
About the editors	XV
List of contributors	XVI
1 On the solid-state theoretical description of photonic crystals (<i>K. Busch, M. Diem, M. Frank, A. Garcia-Martin, F. Hagmann, D. Hermann, S. Mingaleev, S. Pereira, M. Schillinger, and L. Tkeshelashvili</i>)	1
1.1 Introduction	1
1.2 Photonic band structure computation	2
1.2.1 Density of states	4
1.2.2 Group velocity and group velocity dispersion	5
1.3 Nonlinear photonic crystals	6
1.4 Finite structures	8
1.5 Defect structures in photonic crystals	12
1.5.1 Maximally localized photonic Wannier functions	13
1.5.2 Wannier description of defect structures	15
1.5.3 Localized cavity modes	16
1.5.4 Dispersion relations of waveguides	17
1.5.5 Light propagation through photonic crystal circuits	19
1.6 Conclusions	20
References	21
2 Spontaneous emission in photonic structures: Theory and simulation (<i>G. Boedeker, C. Henkel, Ch. Hermann, and O. Hess</i>)	23
2.1 Introduction	23
2.2 Basic concepts	24
2.2.1 Fermi's Golden Rule	24
2.2.2 Beyond the simple picture	27
2.2.3 Coherent tuning of spontaneous decay	28
2.2.4 QED in a structured continuum	29
2.3 Simulations	33
2.3.1 Frequency domain	33
2.3.2 Time domain	36
2.4 Concluding remarks	38
References	40

3	Semiconductor optics in photonic crystal structures	43
	<i>(T. Meier and S. W. Koch)</i>	
3.1	Introduction	43
3.2	Semiclassical theory	44
3.2.1	Light–matter coupling	44
3.2.2	Generalized Coulomb potential	44
3.2.3	Hamilton operator	48
3.2.4	Equations of motion	49
3.3	Numerical results	51
3.3.1	Linear exciton absorption	51
3.3.2	Coherently excited inhomogeneous populations	54
3.3.3	Quasi-equilibrium inhomogeneous populations and nonlinear absorption	55
3.3.4	Coherent wave packet dynamics versus dephasing and thermalization	58
3.4	Summary and outlook	61
	References	62
4	Electrochemically-prepared 2D and 3D photonic crystals	63
	<i>(R.B. Wehrspohn, J. Schilling, J. Choi, Y. Luo, S. Matthias, S. L. Schweizer, F. Müller, U. Gösele, S. Lölkes, S. Langa, J. Carstensen, and H. Föll)</i>	
4.1	Introduction	63
4.2	Materials	64
4.2.1	Porous silicon	64
4.2.2	Porous alumina	67
4.2.3	Porous III–V semiconductors	68
4.3	Application to photonic crystals	69
4.3.1	Introduction	69
4.3.2	2D photonic crystals made of macroporous silicon	70
4.3.3	Photonic defects in electrochemically–prepared 2D photonic crystals	73
4.3.4	3D photonic crystals made of macroporous silicon	75
4.3.5	2D photonic crystals made of porous alumina	78
4.3.6	1D photonic crystals made of InP	78
4.3.7	2D photonic crystals made of InP	79
4.3.8	3D photonic crystals made of InP and GaAs	81
4.4	Summary	81
	References	82
5	Optical properties of planar metallo–dielectric photonic crystals	85
	<i>(A. Christ, S. Linden, T. Zentgraf, K. Schubert, D. Nau, S.G. Tikhodeev, N.A. Gippius, J. Kuhl, F. Schindler, A.W. Holleitner, J. Stehr, J. Crewett, J. Lupton, T. Klar, U. Scherf, J. Feldmann, C. Dahmen, G. von Plessen, and H. Giessen)</i>	
5.1	Introduction	85
5.2	Optical characterization of individual gold nanodisks	86
5.3	Observation of Rayleigh anomalies in metallo–dielectric nanostructures	87
5.3.1	Metallic nanoparticle arrays	87
5.3.2	Metallic nanowire arrays	90

5.4	Waveguide–plasmon polaritons: Strong coupling in a metallic photonic crystal	94
5.4.1	Metallic nanoparticle arrays on dielectric waveguide substrates	94
5.4.2	Metallic nanowire arrays on dielectric waveguide substrates	97
5.4.3	Ultrafast dynamics of waveguide-plasmon polaritons	101
5.5	A polymer DFB laser based on a metal nanoparticle array	103
5.6	Summary	106
	References	107
6	Preparation of 3D photonic crystals from opals	
	<i>(M. Egen, R. Zentel, P. Ferrand, S. Eiden, G. Maret, and F. Caruso)</i>	109
6.1	Introduction	109
6.2	Preparation of monodisperse colloids	110
6.2.1	General methods	110
6.2.2	Preparation of functional core shell structures	115
6.3	Crystallization into opaline structures	120
6.3.1	Sedimentation	120
6.3.2	Crystallization mediated by the magnetic field	120
6.3.3	Two dimensional crystallization to photonic crystal films	121
6.4	Structured photonic crystals	125
6.4.1	Lateral patterning	125
6.4.2	Preparation of heterostructures from different colloids	125
6.5	Replica from opaline structure	127
	References	128
7	Light emitting opal–based photonic crystal heterojunctions	
	<i>(S. G. Romanov, N. Gaponik, A. Eychmüller, A. L. Rogach, V. G. Solovyev, D. N. Chigrin, and C. M. Sotomayor Torres)</i>	132
7.1	Introduction	132
7.2	Experimental techniques and material preparation	135
7.2.1	Measurement techniques	135
7.2.2	Preparation of hetero–opals	136
7.2.3	Selective impregnation of hetero–opals with luminescent nanocrystals	138
7.3	Reflectance and transmission spectra of hetero–opals	140
7.3.1	Observation of two Bragg band gaps	140
7.3.2	The interface gap	141
7.4	Light emission in hetero–opals	145
7.4.1	Anisotropy of photoluminescence in hetero–opals	145
7.4.2	Emission modification at the interface	147
	References	151
8	Three–dimensional lithography of Photonic Crystals	
	<i>(A. Blanco, K. Busch, M. Deubel, C. Enkrich, G. von Freymann, M. Hermatschweiler, W. Koch, S. Linden, D.C. Meisel, and M. Wegener)</i>	153
8.1	Introduction	153
8.2	Holographic lithography	154

8.2.1	The photoresist	155
8.2.2	The crystallography of multiple-beam interference patterns	155
8.2.3	Experimental realization	158
8.2.4	Optical properties of the photoresist structures	160
8.3	Direct laser writing	161
8.3.1	Multi-photon polymerization	162
8.3.2	Experimental realization	164
8.3.3	Direct laser writing of three-dimensional photonic crystals	165
8.3.4	Optical characterization	167
8.4	Templates infiltration	168
8.4.1	Silicon CVD	169
8.4.2	Electrochemical deposition	171
8.5	Conclusions	172
	References	172
9	Tunable photonic crystals using liquid crystals	
	<i>(H.-S. Kitzerow and J.P. Reithmaier)</i>	174
9.1	Introduction: Concepts of tunable photonic crystals	174
9.2	Properties of liquid crystals	178
9.3	Spatially periodic LCs and colloidal crystals	180
9.3.1	Periodic liquid crystals	180
9.3.2	Colloidal crystals containing LCs	182
9.3.3	Polymer-dispersed liquid crystals	185
9.4	Microstructured semiconductors	186
9.4.1	Macroporous silicon	186
9.4.2	Group III-V semiconductors	187
9.5	Summary and perspectives	192
9.5.1	Possible applications of macroporous silicon	192
9.5.2	Possible applications for tunable planar III/V-semiconductor photonic crystals	193
	References	194
10	Microwave modelling of photonic crystals	
	<i>(W. Freude, G.-A. Chakam, J.-M. Brosi, and Ch. Koos)</i>	198
10.1	Fundamentals	198
10.1.1	Maxwell's equations and scaling laws	199
10.1.2	Numerical tools	202
10.2	Microwave measurements	202
10.2.1	Scattering matrix	202
10.2.2	Microwave equipment	203
10.2.3	Coupling of coaxial metallic to dielectric strip waveguide	204
10.3	Loss measurement of waveguide resonator	207
10.4	Experimental results	209
10.4.1	2D infinite-height PhC	210
10.4.2	2D finite-height PhC with line-defect waveguide	210
	References	212

11 Scanning near-field optical studies of photonic devices

<i>(V. Sandoghdar, B. Buchler, P. Kramper, S. Götzinger, O. Benson, and M. Kafesaki)</i>	215
11.1 Introduction	215
11.2 Scanning near-field optical microscopy (SNOM)	215
11.2.1 Brief historical background	215
11.2.2 The operation principle of SNOM	216
11.2.3 Instrumentation	217
11.2.4 Various modes of SNOM operation	218
11.3 Imaging photonic devices with SNOM	219
11.3.1 The evanescent field on a prism	219
11.3.2 SNOM on whispering-gallery resonators	220
11.3.3 Interferometric SNOM measurements	222
11.3.4 Photonic crystals	224
11.4 Manipulating photonic devices with SNOM	233
11.5 Conclusion	234
References	235

12 Application of photonic crystals for gas detection and sensing

<i>(R.B. Wehrspohn, S. L. Schweizer, J. Schilling, T. Geppert, C. Jamois, R. Glatthaar, P. Hahn, A. Feisst, and A. Lambrecht)</i>	238
12.1 Principle	238
12.2 Realizations with 3D photonic crystals	241
12.3 Conclusion	245
References	245

13 Polymeric photonic crystal lasers

<i>(K. Forberich, S. Riechel, S. Pereira, A. Gombert, K. Busch, J. Feldmann, and U. Lemmer)</i>	247
13.1 Introduction	247
13.2 Fabrication of microstructured surfaces by interference lithography	247
13.2.1 Interference lithography	248
13.2.2 Replication and subsequent substrate processing	250
13.3 Active materials for organic photonic crystal lasers	252
13.4 Lasing in two dimensional polymeric photonic crystals	254
13.5 Semiclassical theory of lasing in surface relief structures	256
13.5.1 Semiclassical laser theory in structured media	257
13.5.2 Effective 2D model for surface relief structures	260
13.5.3 Discussion of lasing behavior in surface relief structures	261
13.6 Conclusions	263
References	264

14 Photonic crystal fibers

<i>(J. Kirchhof, J. Kobelke, K. Schuster, H. Bartelt, R. Iliew, C. Etrich, and F. Lederer)</i>	266
14.1 Introduction	266
14.2 Modeling of photonic crystal fibers	267

14.2.1	Plane wave expansion methods	269
14.2.2	The localized functions method	271
14.2.3	The finite element method (FEM)	272
14.2.4	The multipole method	272
14.2.5	Propagation methods	273
14.3	Fiber technology	275
14.3.1	Preparation of photonic crystal fibers	275
14.3.2	Fluid–dynamic aspects in the preparation of photonic crystal fibers	276
14.4	Special properties of photonic crystal fibers	278
14.4.1	Spectral transmission	278
14.4.2	Variation of the numerical aperture and the mode profil	280
14.4.3	Dispersion properties	282
14.4.4	Mechanical properties	283
14.5	Overview of applications	284
14.6	Conclusions	286
	References	286
15	Photonic crystal optical circuits in moderate index materials (<i>M. Augustin, G. Böttger, M. Eich, C. Etrich, H.-J. Fuchs, R. Iliew, U. Hübner, M. Kessler, E.–B. Kley, F. Lederer, C. Liguda, S. Nolte, H.G. Meyer, W. Morgenroth, U. Peschel, A. Petrov, D. Schelle, M. Schmidt, A. Tünnermann, and W. Wischmann</i>)	289
15.1	Motivation	289
15.2	Design of the PhC films	291
15.3	Photonic crystal waveguides in niobiumpentoxide	292
15.4	Photonic crystals in polymer films	297
15.5	Conclusions	304
	References	306
16	Planar high index-contrast photonic crystals for telecom applications (<i>R. März, S. Burger, S. Golka, A. Forchel, C. Hermann, C. Jamois, D. Michaelis, and K. Wandel</i>)	308
16.1	Introduction and motivation	308
16.2	Waveguide losses	309
16.3	Efficient analysis of photonic crystals	312
16.4	Patterning of photonic crystals	314
16.5	Sources for multi-channel WDM–transmitters	318
16.6	Photonic crystal superprisms for WDM–applications	320
16.7	PhC–based dispersion compensator	323
16.8	Fiber–to–chip coupling of photonic crystals	325
	References	327
17	Photonic crystal based active optoelectronic devices (<i>M. Kamp, T. Happ, S. Mahnkopf, A. Forchel, S. Anand, and G.–H. Duan</i>)	329
17.1	Introduction	329
17.2	Waveguide based 2D photonic crystals	330

17.3 Semiconductor lasers with photonic crystal mirrors 332
 17.3.1 Fabrication 333
 17.3.2 Device performance 336
 17.3.3 Single mode photonic crystal based lasers 336
17.4 All photonic crystal lasers 339
17.5 Tunable photonic crystal lasers 342
17.6 Conclusion 345
References 346

Appendix

A List of abbreviations 347
B Conventions 348
Index 349

Preface

The semiconductor revolution, that began in the late 1940's, enabled profound and unanticipated improvements in our standard of living. These artificial electronic materials, that control the flow of electrons on a microscopic scale, remain a centerpiece of today's micro-electronics industry. Likewise, the invention of the laser in the early 1960's, inspired the development of artificial materials that mold the flow of light. The photonics industry has irrevocably enhanced the way we transmit information, through the replacement of electronic signals in wires, with laser pulses in optical fibers. Along this course of scientific and technological progress, it is tempting to ask whether there exists a photonic analogue of the electronic semiconductor micro-chip. This requires the design and fabrication of practical photonic materials that can localize light and mold its flow on an equivalently microscopic scale. The collection of articles in this book describes significant research developments in Germany towards this objective.

Photonic band gap (PBG) materials are a novel class of photonic crystals that carry the concept of molding the flow of light to the most microscopic level allowed by the laws of physics. Consisting of dielectric microstructures with periodicity of roughly half the wavelength of light, PBG materials scatter photons in a manner similar to the scattering of electrons by the crystalline array of atoms in a semiconductor. The resulting gap in the electromagnetic spectrum provides a unique environment in which unwanted pathways for electromagnetic wave propagation are removed and desired ones can be selectively engineered, through defects in the photonic crystal lattice. In this way, a PBG material provides a robust platform for the integration of passive optical circuitry and active light emitting devices onto a compact optical micro-chip. Moreover, the electromagnetic density of states on the optical micro-chip can be engineered through suitable crystal defect architectures. This enables highly frequency selective changes in the rate of spontaneous emission of light from atoms whose resonance frequency lies within the engineered electromagnetic vacuum. This provides a new frontier in the field of quantum optics. The possibilities outlined above have inspired a worldwide effort to design, fabricate, and characterize a variety of different types of photonic crystals.

Research efforts in Germany have played a leading role in the worldwide effort to realize the promise of photonic band gap materials. These include the fabrication of two-dimensional and three-dimensional photonic crystals of unprecedented aspect ratio, in single crystal semiconductors such as silicon, using photo-electrochemical etching. These crystals have provided a platform for pioneering optical experiments both within Germany and internationally. Other novel photonic band gap architectures may soon be achieved through direct optical "writing" using two-photon absorption and holographic lithography in a polymer-based template, followed by replication (inversion) of the template with polycrystalline semiconductors. On the

theoretical side, efficient modeling of electromagnetic wave propagation in complex defect architectures is an essential prerequisite to the design and fabrication process. This prominent role for theory is made possible through the essentially perfect applicability of Maxwell's equations to the optical properties of photonic crystals, without additional complicating interactions such as electron-electron and electron-phonon interactions that arise in the electronic properties of solids. Nevertheless the complex geometries of photonic crystal defect architectures and their concomitant light localization effects, call for the development of novel computational approaches. One of these, described in this book, is the introduction of Wannier functions (the optical analogue of localized atomic orbitals in solid state physics) as the basis functions for electromagnetic wave propagation. These localized basis functions may be indispensable for efficiently describing optical propagation within optical circuit architectures of three-dimensional PBG materials. Finally, a number of practical applications of photonic crystals is beginning to appear. Two particularly interesting and unique developments are the use of photonic crystals as mirrors and couplers for practical III-V semiconductor based lasers and the integration of a number of such lasers within a photonic crystal micro-chip.

It is clear from the above illustrations that photonic crystal research in Germany has provided a number of important, first-of-its-kind in the world, achievements. This book provides the reader with a valuable introduction to a number of these developments and an overview of a number of other emerging research directions.

Sajeev John

Toronto, December 2003

About the editors

Kurt Busch has been an Associate Professor at the Department of Physics and the School of Optics: CREOL & FPCE at the University of Central Florida (Orlando, USA) since January 2004. He received his undergraduate (Dipl.-Phys.; 1993) and postgraduate training (Dr. rer. nat.; 1996) at the University of Karlsruhe (Germany) and partly at the Iowa State University (Ames, USA). His professional experience included working at Iowa State University (Ames, USA), the University of Toronto (Canada; 1997-1999) and leading a junior research group within the Emmy-Noether program of the Deutsche Forschungsgemeinschaft at the University of Karlsruhe (Germany; 2000-2003). His research interests lie in light-matter interactions and wave propagation in strongly scattering materials and Photonic Crystals.

Stefan Lölkes graduated in semiconductor physics at the Technical University of Munich, Germany, in 2000. In 2001, he started his Ph.D. thesis on “Electrochemical etching of Photonic Crystals” at the Chair for General Materials Science at the Christian-Albrechts-University of Kiel, Germany. In parallel, he co-organized already several national symposia on Photonic Crystals in the framework of the DFG priority program 1113 “Photonic Crystals”.

Ralf B. Wehrspohn received his diploma degree in physics at the University of Oldenburg in 1995. He then carried out a Ph.D. at the Ecole Polytechnique in France about thin film technology and electrochemistry. In 1998 he joined the Philips Research Laboratories in Redhill, U.K., to work on thin film transistors for AMLCD. From end of 1999 to March 2003 he has been responsible for the activities on photonic crystals and self-ordered porous materials at the Max-Planck-Institute of Microstructure Physics in Halle. Since April 2003 he is full professor in experimental physics at the University of Paderborn where he leads the activities on nanophotonic materials. R. B. Wehrspohn has been awarded with the Heinz Maier-Leipnitz award of the DFG and the TR100 innovation price of the MIT in 2003.

Helmut Föll received his Ph.D. degree in Physics in 1976 from the University of Stuttgart in conjunction with the Max-Planck-Institute for Metal Research in Stuttgart. After post-doctoral work at the Department of Materials Science and Engineering at Cornell University and a position as guest scientist at the T.J. Watson Res. Center of IBM in Yorktown Heights, he joined Siemens in 1980, working in the newly founded Solar Energy Department of Central Research in Munich. After various senior positions in microelectronics development, in 1991 he accepted an offer of the Christian-Albrechts-University of Kiel to become the founding dean of the newly established Faculty of Engineering, where he also holds the Chair for General Materials Science. Since 1998 he is back to research, with particular interest in solar cell technology and the electrochemistry of semiconductors. He is one of the pioneers in the field of porous semiconductors and has coauthored more than 150 papers and 20 patents.

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- chromatic 323
- compensator 323
- slope 323
- W1-waveguide (SOI) 324
- dispersion relation
 - strip waveguide 204
- distributed feedback resonators 254
- DOS
 - anisotropic model 26
 - band edge singularities 26
 - projected LDOS 24
- effective 2D model 260
- effective Hamiltonian 99
- effective mass approximation 26
- effective nonlinearity 7
- effective parameters 256
- elastic properties of liquid crystals 178
- electrochemical deposition 171
- electron beam lithography 187–189
- electron cyclotron resonance (ECR) enhanced
 - etching 316
- electron population 51, 54
- electron-beam lithography 125
- EM field continuity 134, 144
- emission spectra 105
- empty-lattice approximation 89, 93
- equations
 - Maxwell–Bloch 256
- etching 186, 188, 189
 - AlGaAs 318
 - chemically assisted ion beam (CAIBE) 316
 - electrochemical 63
 - electron cyclotron resonance (ECR) enhanced 316
 - inductively coupled plasma (ICP) 316
 - large area 65
 - SOI 318, 319
- etching depth 291–293, 298–300, 302, 305
- exciton 44, 53
 - binding energy 47
- extinction 91
- Fabry–Perot-resonances 74, 140, 142
- FDTD *see* finite-difference-time-domain calculation
- ferroelectric liquid crystals 194
- fiber technology 275
- fiber-to-chip coupling 325
- field computation
 - boundary elements 34
 - frequency domain 33
- filling factor 157, 160
- filter PL 136, 145–147
- finite difference time domain 142–144, 273
- finite element method 267
- finite element solvers 312
- finite-difference-time-domain calculation
 - 36, 310
 - out-of-plane losses 292, 300, 305
 - PhC slab waveguide transmission 299, 300
 - PhC waveguide bend 296, 297
- finite-height PhC *see* photonic crystal
- fluorescent dyes 114
- focal point 150
- form factor 157
- frequency domain propagation 313
- full band gap 109, 127
- functional colloids 114
- GaAs, porous 64, 68, 81
- gain 56
- gas sensor 238
- generalized Coulomb potential 46
- gold nanodisks 87, 94, 104
- grating
 - binary superimposed (BSG) 320
- gratings
 - surface relief 247
- group velocity 5, 239
 - dispersion 5
- heterojunction 132, 134, 135, 142–144, 149, 151
- heterostructures 125
- high-delta fiber 266
- hole population 51, 54
- holey fiber 266
- holographic lithography 154
- ICP etching system 316
- III–V semiconductors, porous 63, 68, 78
- impedance matching 326
- inductively coupled plasma (ICP) etching 316
- InGaAsP
 - W1-waveguide 311

- InGaAsP/InP
 - superprism 320
- inhomogeneous carrier populations 54
- infinite-height PhC *see* photonic crystal
- inorganic colloids 110
- InP, porous 64, 68, 78
- interband polarization 49, 51
- interconnectivity conditions 158
- interface gap 132, 141, 143
- interface minimum 141–144
- interference lithography 247
- interference pattern 155
- inverted opal 37, 176, 183, 185
- isophote 163
- ITO 86

- kp perturbation theory 5

- laser 39
 - direct writing 161
 - multi-segment 318
 - semiclassical theory 256
 - widely tunable 318
- lateral patterning 125
- lattice
 - bcc 156
 - Bravais 156
 - fcc 156, 158
 - hexagonal 66, 67, 79
 - honeycomb 67
 - real space 156
 - reciprocal 156
 - simple cubic 76
 - square 67
- layer-by-layer
 - deposition 138, 151
 - structure 165
- LDOS 24, 35, 38
- leaky modes 268
- light cone 93
- light–matter interaction 44, 49
- linear absorption 47, 53
- local density of states 5
- localized functions 267
- loss *see* microwave material, 280
 - factor 199
 - measurement 209
 - per medium wavelength 199
 - scattering 209
- losses
 - W1–waveguide 309
- low loss materials 289, 290, 305

- macroporous silicon 228, 241
- Markov approximation 30
- matching
 - phase, spot, impedance 326
- material *see* microwave material, dielectric constant
- Maxwell’s equations 199
 - scaling the dielectric constant 200
 - scaling the structure 198, 200
- metallo–dielectric
 - grating 10
 - photonic crystal 85
- microcavity 75, 176, 190, 193
- microreplication 247
- microresonators
 - and fabrication quality 230
 - and SNOM 228, 233
- microwave 198
 - coaxial feeder 205
 - equipment 203
 - material 201
 - measurement 203, 204, 207, 210, 211
 - vector network analyser 203
- mirror
 - scattering matrix 208
- mode field 281
- modes 268
- moving meniscus 123
- multi–photon
 - absorption 163
 - polymerization 162
- multi–scale
 - analysis 256
 - approach 7
- multipole expansion 267

- nanoimprinting 67
- nanoparticle arrays 87, 94
- nanowire arrays 90, 97
- nematic phase 179, 187
- Niobiumpentoxide, Nb₂O₅ 291–293, 304, 305
- non–silica 278
- nonlinear absorption 56
- nonlinear polarization 6

- nonlinear Schrödinger equation 7
- numerical aperture 280
- numerical modeling 135
- numerics
 - FDTD 202
 - FE 202
- opal, artificial 109
- particle plasmon 86
- patterned substrates 125
- PDLC *see* polymer-dispersed liquid crystals
- perfectly matched layer (PML) 272, 310
- permittivity *see* microwave material, dielectric constant
- phase matching 326
- photobleaching 298, 302, 303, 305
- photoinitiator 155
- photonic band gap
 - complete 76, 77
- photonic band gap fiber 266
- photonic crystal 189, 190, 241
 - 1D 26, 78
 - 2D 69, 70, 78, 79
 - 2D crystal 33
 - 2D finite-height
 - line-defect waveguide 210
 - line-defect waveguide loss 212
 - measurement 212
 - microwave model 210
 - 2D infinite-height
 - band diagram 211
 - measurement 211
 - microwave model 211
 - transmission 211
 - 3D 75, 81
 - bulk 70
 - circuit 19
 - finite 72
- photonic crystal fiber 266
- photoresist (SU-8) 155
- PL intensity ratio 146, 149
- planar defect 133, 134
- planar photonic crystals 187, 193
- plane wave expansion 267
- plane wave method 3
- plano-convex lens (Si) 326
- plasma enhanced chemical vapor deposition (PECVD) 317
- polariton splitting 96, 97
- polyelectrolyte multilayers 117
- polymer 297–299, 301, 302
- polymer colloids 111
- polymer-dispersed liquid crystals 185
- polymerization
 - cationic 155
 - radical 155
- polymers
 - conjugated 247
- pore
 - crystallographical 79
 - currentline 79
 - diameter modulation 75, 81
- post-exposure bake 158
- preform 275
- propagation constant 268
- propagation loss of slab waveguides 289
- quantum cascade lasers 245
- quantum electrodynamics (QED) 24, 29
- quantum optics 23
 - multiphoton states 32
 - strong coupling 28
 - weak coupling 24
- quantum well 47, 53
- quantum wire 55
- radiated power 148
- radiation losses 290, 305
- Rayleigh
 - anomalies 87, 92
 - scattering 289
- reflection 11
- reflection spectrum 167
- refractive index 112
 - high 289
 - moderate to low 289, 290, 297, 299, 302, 304, 305
 - negative 314
 - tuning of 297, 305
- replica 127
- resonance fluorescence 28, 32
- resonant condition 133
- resonator 290, 301–303
- rotating wave approximation 29
- saturation threshold 132, 147–149
- scaling *see* Maxwell's equations

- scattering matrix 8, 90, 99, 203
 - mirror 208
 - transmission line 208
- sedimentation 120
- self energy 49
- self-organization 66, 67, 79, 81, 109, 132, 133, 151
- semiconductor 174, 186, 187
 - Bloch equations 50
 - laser 57
 - organic 247
- sensor 238
- shrinkage 158
- silica 280
- silicon
 - macroporous 63, 64, 70, 75, 185–187, 192
 - mesoporous 64, 66
- Silicon CVD 169
- silicon optical bench (SiOB) 326
- slowly varying envelope approximation 8
- SNOM
 - and interferometry 222
 - and manipulation of sample 234
 - and pulse tracking 223
 - influence of probe 233
 - modes 218
 - principle 216
 - prism 219
 - resolution 229
 - shear force control 218
 - whispering-gallery resonators 220
- SNOM and photonic crystals
 - comparison to FDTD models 230
 - fabrication quality 230
 - measuring waveguide loss 228
 - scattered light 225
 - theoretical treatments 225
 - waveguide bends 227
- soft bake 158
- SOI
 - etching 318, 319
 - W1-waveguide 310
- source PL 136, 145–148, 150
- spontaneous emission 24
 - nonexponential decay 29, 32
 - optical tuning 28
- spot 326
- strong coupling 94
- superprism 290, 291
 - InGaAsP/InP 320
- surface-plasmon polaritons 85
- surfactant free emulsion polymerization 112
- taper 240, 326
- template infiltration 168
- thermal stability 112, 114
- thermalization 58, 61
- thin opal film 133, 135
- threshold
 - dose 155, 157
 - irradiation 155
- time-dependent Hartree–Fock approximation 50
- time-harmonic analysis 313
- tolerancing 312
- transition
 - between strip and PhC waveguide 209, 212
- translational symmetry 156
- transmission 11, 278
 - line *see* scattering matrix, transmission line
 - spectrum 161, 167
- trigonal structure 158
- tunable
 - band gap 174
 - laser 318
 - resonance 190
- tuning 28, 245
- two dimensional crystallization 121
- ultrafast dynamics 101
- umbrella-like configuration 158
- uncoupled bands 12
- voxel 163
- W1-waveguide 309
 - dispersion (SOI) 324
 - InGaAsP 311
 - SOI 310
- Wannier functions 13
- wave packet dynamics 61
- waveguide 17, 74, 94
 - bend 20, 290, 295–297, 305
 - coaxial feeder 205
 - dispersion of strip 204