

Tunable Micro-optics

Presenting state-of-the-art research into the dynamic field of tunable micro-optics, this is the first book to provide a comprehensive survey covering a varied range of topics including novel materials, actuation concepts, and new imaging systems in optics. Internationally renowned researchers present a diverse range of chapters on cutting-edge materials, devices, and subsystems, including soft matter, artificial muscles, tunable lenses and apertures, photonic crystals, and complete tunable imagers. Special contributions also provide in-depth treatment of micro-optical characterization, scanners, and the use of natural eye models as inspiration for new concepts in advanced optics. With applications extending from medical diagnosis to fiber telecommunications, *Tunable Micro-optics* equips readers with a solid understanding of the broader technical context through its interdisciplinary approach to the realization of new types of optical systems. This is an essential resource for engineers in industry and academia, and advanced students working on optical systems design.

Hans Zappe is the Gisela and Erwin Sick Chair of Micro-optics at the University of Freiburg, and an internationally recognized teacher and researcher in micro-optics. He has twenty-five years' experience working on optical microsystems, integrated optics, and semiconductor lasers and has previously authored three textbooks.

Claudia Duppé was Administrative Program Manager of the DFG Priority Program "Active Micro-optics" at the University of Freiburg. She holds a PhD in New Zealand literature and has focussed professionally on academic communication and science management. She is presently Head of Communication and Networking at the Catholic University of Applied Sciences Freiburg.

Cambridge University Press
978-1-107-03245-3 - Tunable Micro-Optics
Edited by Hans Zappe and Claudia Duppe
Frontmatter
[More information](#)

Cambridge University Press
978-1-107-03245-3 - Tunable Micro-Optics
Edited by Hans Zappe and Claudia Duppe
Frontmatter
[More information](#)

Tunable Micro-optics

Edited by

HANS ZAPPE

University of Freiburg

CLAUDIA DUPPÉ

University of Freiburg



Cambridge University Press
978-1-107-03245-3 - Tunable Micro-Optics
Edited by Hans Zappe and Claudia Duppé
Frontmatter
[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/9781107032453

© Cambridge University Press 2016

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 2016

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

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

Library of Congress Cataloguing in Publication data

Zappe, Hans

Tunable micro-optics / Hans Zappe, University of Freiburg, Claudia Duppé,
University of Freiburg.

pages cm

Includes bibliographical references and index.

ISBN 978-1-107-03245-3 (hardback)

1. Tunable microlenses. 2. Optics, Adaptive. 3. Micro-optics.

I. Duppé, Claudia. II. Title.

TA1660.5.Z37 2016

621.36-dc23 2015028154

ISBN 978-1-107-03245-3 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
978-1-107-03245-3 - Tunable Micro-Optics
Edited by Hans Zappe and Claudia Duppe
Frontmatter
[More information](#)

We thank our families for putting up with all the nonsense that kept us busy throughout this project. You guys always put our focus right.

Thomas, Helen and Nele,

Frances and Max.

Cambridge University Press
978-1-107-03245-3 - Tunable Micro-Optics
Edited by Hans Zappe and Claudia Duppe
Frontmatter
[More information](#)

Contents

<i>List of contributors</i>	<i>page xvii</i>
<i>List of acronyms</i>	<i>xxiii</i>

Part I Introduction	1
1 Tunable Micro-optics	3
Hans Zappe	
1.1 Introduction	3
1.2 Microlenses	3
1.2.1 Liquid Microlenses	4
1.2.2 Hydraulic Microlenses	10
1.2.3 Hydrodynamic Microlenses	15
1.2.4 Deformable Microlenses	16
1.2.5 Liquid Crystal Microlenses	18
1.3 Attenuators	19
1.3.1 Mechanical Attenuators	19
1.3.2 Fluidic Attenuators	21
1.4 Irises	21
1.4.1 Mechanical Irises	22
1.4.2 Fluidic Irises	23
1.5 Filters	24
1.5.1 Mechanically Tunable Filters	24
1.5.2 Thermally Tunable Filters	25
1.5.3 Chemically Tunable Filters	26
1.6 Diffractive Optics	27
1.6.1 Gratings	27
1.6.2 Fresnel Lenses	29
1.6.3 Other Diffractive Structures	29
1.7 Outlook	29
References	30

2	Tunable Optics in Nature	38
	Robert Brunner and Erik Förster	
2.1	Introduction	38
2.2	Movements of the Entire Eye	40
2.2.1	Continuous Eye Movements	40
2.2.2	Retinal Specialization and Saccadic Eye Movement	42
2.3	Distance Adjustment and Adapting Vision to Amphibious Conditions	45
2.3.1	Accommodation in Human Eyes: Example for Terrestrial Eyes	46
2.3.2	Accommodation in Fish Eyes: Representative for Aquatic Eyes	50
2.3.3	Chameleon Eyes: Accommodation as a Distance Cue	54
2.3.4	Accommodation in Diving Seabirds	55
2.4	Final Remarks	60
	References	61
	Part II Devices and materials	65
3	Soft-Matter Micro-optics	67
	Wolfgang Mönch	
3.1	Introduction	67
3.2	Soft-Matter Micro-optics Based on Wetting Effects	69
3.2.1	Basic Equations	69
3.2.2	Actuation Mechanisms	71
3.2.3	Liquid Lenses	73
3.2.4	Systems and Applications	77
3.3	Soft-Matter Micro-optics Based on Elasticity	80
3.3.1	Elasticity Effects	80
3.3.2	Elastomer-Membrane Lenses	81
3.3.3	Other Developments in Elastomer Optics	84
3.4	Conclusion and Summary	86
	References	88
4	Tunable Reflective Optics	92
	David Dickensheets	
4.1	Introduction	92
4.2	History of Tunable Reflective Optics	93
4.3	Scanning and Pointing Mirrors (First-Order Phase Modulation)	94
4.3.1	Tilt Mirror Performance Metrics	95
4.3.2	MEMS Pointing and Scanning Mirrors	96
4.3.3	Mirror Designs for Greater Angular Scan Range	97
4.4	Focus Control Mirrors (Second-Order Phase Modulation)	100
4.4.1	Focusing Mirror Performance Metrics	100
4.4.2	MEMS Deformable Mirrors for Focus Control	101

Contents

ix

4.4.3	Maintaining Diffraction-Limited Performance During Focus Adjustment	103
4.4.4	3D Scan Mirrors for Simultaneous Control of the x, y, z Position of the Beam Focus	105
4.4.5	Toward Greater Membrane Stroke and High-Resolution Focus Control	106
4.5	Aberration Correction Mirrors (Higher-Order Phase Modulation)	109
4.6	Other Tunable Reflective Optics	112
4.6.1	Spatial Light Modulators	113
4.6.2	Tunable Diffractive Optics	113
4.7	Looking Ahead	115
	Acknowledgment	116
	References	116
5	Tunable Liquid Lenses	123
	J. Andrew Yeh and Yen-Sheng Lu	
5.1	Introduction	123
5.2	Mechanisms for Focal Length Tuning	124
5.3	Liquid Lens Design	126
5.3.1	Droplet as a Lens	126
5.3.2	Liquid Interfaces	126
5.3.3	Gravitational Effect	127
5.3.4	Temperature Effect	128
5.3.5	Centering of Optical Axis	128
5.3.6	Driving Voltage	129
5.3.7	Liquid Composition	130
5.3.8	Scaling	130
5.3.9	Packaging	130
5.4	Liquid Lenses	131
5.4.1	Mechanically Driven Liquid Lens	131
5.4.2	Electrically Driven Liquid Lenses	136
5.5	Applications	148
5.5.1	3D Illumination System	148
5.5.2	Correction of Presbyopia	148
5.5.3	Biomedical Imaging	150
5.6	Conclusion	151
	References	152
6	Optofluidic Micro-shutters and Micro-irises	156
	Philipp Müller	
6.1	Introduction	156
6.1.1	Importance of Tunable Apertures	157
6.2	Fundamental Microfluidic Concepts	157

6.2.1	Liquids in the Microdomain	157
6.2.2	Liquids Adopt Minimal Surfaces	158
6.2.3	Electrowetting-on-Dielectrics as an Effective Micro-actuation Mechanism	159
6.3	State-of-the-Art of Optofluidic Tunable Apertures	160
6.4	Integrated Optofluidic Micro-shutter	164
6.4.1	Device Structure and Working Principle	164
6.4.2	Double Actuator Design	165
6.4.3	Fabrication	166
6.4.4	Measurements and Results	166
6.5	Integrated Optofluidic Micro-iris	167
6.5.1	Device Structure and Working Principle	167
6.5.2	Technological Aspects	169
6.5.3	Fabrication	169
6.5.4	Measurements and Results	169
6.6	Summary and Conclusion	172
	References	173
7	Solid Body Elastomeric Lenses	176
	Sebastian Petsch, Peter Liebetaut, and Hans Zappe	
7.1	Introduction	176
7.2	Concept	177
7.3	Fabrication	178
7.3.1	Materials	178
7.3.2	Reaction Injection Molding	179
7.3.3	Doublet Fabrication	183
7.4	Actuation Techniques	183
7.5	Achromatic Doublet Lens	186
7.5.1	Design and Fabrication	186
7.5.2	Measurement Setup	187
7.5.3	Characterization	187
7.6	Tunable Focal Length	188
7.6.1	Simulation	189
7.6.2	Characterization	189
7.7	Tunable Aberrations	191
7.7.1	Un-actuated Characteristics	192
7.7.2	Tunable Astigmatism	192
7.8	Summary and Outlook	195
	References	196
8	Spatially Tunable Polarization Devices	197
	Frederik Schaal, Michael Rutloh, Susanne Weidenfeld and Wolfgang Osten	
8.1	Introduction	197

Contents

xi

8.2	System Design Overview	198
8.3	Photo Addressable Cell (PAC)	199
8.3.1	State-of-the-Art	200
8.3.2	Red Absorbing Azobenzenes and Their Photo-Isomerization	202
8.3.3	Photo-orientation of Films with Azobenzene Chromophores	203
8.3.4	Photoreversible Polarization Elements	204
8.3.5	Reversible Photo-alignment Based on Polyurethane Films	205
8.3.6	Reversible Photo-alignment Based on SAM Layers	206
8.4	Vertical-Cavity Surface-Emitting Laser (VCSEL)	207
8.4.1	VCSEL Fabrication	207
8.4.2	VCSEL Characterization	210
8.5	Four Channel Micro-optical Addressing System	211
8.6	Integration into a Microscope Objective	212
8.7	Application of the System for Tunable Phase Contrast	214
8.8	Summary and Outlook	215
	References	216
9	Aluminum Nitride and Diamond Membranes for Tunable Micro-optics	219
	Steffen Leopold, Fabian Knöbber and Daniel Pätz	
9.1	Introduction	219
9.2	Optical Design	220
9.2.1	Spherical Membrane Bending for Focal Length Tuning	221
9.2.2	Nonspherical Membrane Bending for Enhanced Optical Performance	222
9.3	Aluminum Nitride Membranes for Tunable Micro-optics	223
9.3.1	Mechanical Properties	224
9.3.2	Optical Properties	227
9.3.3	Thermal Properties	228
9.4	Nanocrystalline Diamond Membranes for Tunable Micro-optics	229
9.4.1	Growth of Nanocrystalline Diamond	230
9.4.2	Mechanical Properties of Diamond Membranes	232
9.4.3	Electrical Properties of Diamond Membranes	233
9.4.4	Optical Properties of Diamond Membranes	235
9.5	Conclusion and Outlook	237
	References	237
10	Piezoelectrically Actuated Tunable Microlenses	241
	Jan Draheim and Ulrike Wallrabe	
10.1	Introduction	241
10.2	State of the Art	241
10.3	Minimalist Design for Adaptive Lenses	243
10.3.1	Working Principle	244
10.3.2	Theoretical Behaviour of the System	246

10.4	Materials	248
10.5	Fabrication	250
10.5.1	Fabrication of the Components	250
10.5.2	Priming and Assembly	251
10.6	Characterization	252
10.6.1	Opto-mechanical Behaviour	253
10.6.2	Optical Behaviour	257
10.7	Conclusion	258
	References	259
Part III Systems and Applications		263
11	Characterization of Micro-optics	265
	Heidi Ottevaere, Lien Smeesters, and Hugo Thienpont	
11.1	Introduction	265
11.2	Some Basic Theory	266
11.2.1	Essential Optical Properties of a Tunable Lens	266
11.2.2	Chromatic Aberrations	267
11.2.3	Introduction to Primary or Third-Order Monochromatic Aberrations	268
11.2.4	Quality Criteria for Diffraction-Limited Lens Performance	272
11.3	Overview of Tunable Lens Testing Methods	276
11.3.1	Basic Characteristics of a Tunable Lens	276
11.3.2	Two-Beam Interference	276
11.3.3	Transmitted Light Measurements Using a Mach-Zehnder Interferometer	278
11.4	Optical Characterization of a Voltage-Tunable Lens	282
11.4.1	Plane Wavefront Illumination to Determine the Focal Length Range	284
11.4.2	Spherical Wavefront Illumination to Determine the RMS Wavefront Error	286
11.4.3	Calculation of the Modulation Transfer Function Out of the Wavefront Map	288
11.4.4	Transmission Characteristics of the Tunable Lens	288
11.5	Conclusion and Perspectives	289
	References	290
12	Photonic Crystals	293
	Olav Solgaard and Xuan Wu	
12.1	Introduction	293
12.2	Photonic Crystal Basics	294
12.2.1	Optical Modes in Photonic Crystals	295
12.3	Photonic Crystal Types and Fabrication	299

Contents

xiii

12.3.1	Dielectric stacks	299
12.3.2	Nanobeams	299
12.3.3	Slabs	300
12.3.4	Yablonovite	303
12.3.5	Woodpile	304
12.3.6	Guided Assembly	305
12.4	Tuning of Photonic Crystals	306
12.4.1	Electro-optic Tuning	307
12.4.2	Plasma Effect Tuning	308
12.4.3	Index Tuning of Voids	308
12.4.4	Thermal Tuning	309
12.5	MEMS Photonic Crystal Tuning	310
12.5.1	Photonic Crystal MEMS Scanners	311
12.5.2	Photonic Crystal Fabry-Pérot Resonators	312
12.5.3	Tuning by Evanescent Coupling – Photon Tunneling	313
12.5.4	Tuning by Breaking Symmetry	313
12.5.5	Tuning by Changing Boundary Conditions	314
12.6	Outlook	314
	References	315
13	MEMS Scanners for OCT Applications	319
	Hiroshi Toshiyoshi, Keiji Isamoto, and Changho Chong	
13.1	Introduction	319
13.2	OCT System	320
13.2.1	Time-Domain OCT (TD-OCT)	320
13.2.2	Fourier-Domain OCT (FD-OCT)	321
13.2.3	Comparison of TD-OCT and FD-OCT	322
13.2.4	R&D of MEMS for FD-OCT	324
13.3	MEMS for Wavelength Tunable Source	325
13.3.1	Principle of External Cavity Laser	325
13.3.2	MEMS Scanner with Amplitude Magnification Mechanism	326
13.3.3	MEMS Scanner Fabrication Results	329
13.3.4	FD-OCT Measurement	332
13.4	MEMS for OCT Endoscope	334
13.4.1	Fiber Optic OCT	334
13.4.2	Electrothermal Scanner for OCT Endoscope	335
13.4.3	Electromagnetic Scanner for OCT Endoscope	336
13.4.4	Electrostatic Scanner for OCT Endoscopy	337
13.4.5	Effect of Electrical Shock on Body	337
13.5	All-Optical Fiber Endoscope System	338
13.5.1	Application of WDM System to Endoscope Optics	338
13.5.2	Low-voltage MEMS Scanner for All-Optical OCT	340

13.5.3	All-Optical OCT Results	342
13.6	Summary	343
	References	344
14	Liquid Crystal Elastomer Micro-optics	346
	Sebastian Petsch, Richard Rix, Stefan Schuhladen, Rudolf Zentel, and Hans Zappe	
14.1	Introduction	346
14.2	Liquid Crystal Elastomers	347
14.2.1	Structure	348
14.2.2	Orientation	349
14.2.3	Fabrication and Integration of Heaters	350
14.2.4	Characterization	351
14.3	The Liquid Crystal Elastomer Iris	353
14.3.1	Design and Fabrication	353
14.3.2	Mechanical and Optical Performance	354
14.4	The LCE-Actuated Elastomeric Lens	356
14.4.1	Lens Actuation Concepts	357
14.4.2	LCEs for Lens Actuation	357
14.4.3	Vectored Lens Actuation	358
14.4.4	Symmetric Lens Actuation	361
14.5	Integration: The Engineered Eyeball	363
14.6	Summary and Outlook	365
	References	366
15	Adaptive Scanning Micro-eye	369
	Daniel Pätz, Steffen Leopold, Verena Züribig, and Tobias Deutschmann	
15.1	Introduction	369
15.2	Design of a Tunable Scanning Micro-eye	370
15.2.1	Tunable Zoom System	371
15.2.2	Scanning with Tunable Prism	372
15.2.3	Scanning with Laterally Shifted Cylindrical Lenses	373
15.2.4	Depth of Focus of a Tunable Aperture	374
15.3	Tunable Membrane Lenses and Prisms Fabricated in AlN	376
15.3.1	Tunable AlN Membrane Lenses	376
15.3.2	Tunable Prisms with Electro-Thermal Actuation	378
15.4	Tunable Micro-iris	379
15.4.1	Electrochromism	380
15.4.2	Fabrication	380
15.4.3	Characterization	382
15.5	Multisegment Piezo Lens	384
15.5.1	Design of the Piezo Lens	384
15.5.2	Fabrication	385
15.5.3	Characterization	386

Contents

xv

15.6	Integration of the Scanning Micro-eye	388
15.6.1	Imaging and Scanning with Tunable Cylindrical Lenses	388
15.6.2	Tunable Lens Integration	389
15.6.3	Anamorphic Zoom with Cylindrical Lenses	390
15.6.4	Integration for Multifunctional Actuation	391
15.7	Conclusion and Perspectives	392
	References	393
16	Hyperspectral Eye	395
	Ulrike Wallrabe, Moritz Stürmer, Erik Förster, and Robert Brunner	
16.1	Hyperspectral Imaging	395
16.1.1	The Natural Model	395
16.1.2	Technical Implementation	396
16.2	State-of-the-Art of Adaptive Elements for Hyperspectral Imaging	398
16.2.1	Dispersive Elements	398
16.2.2	Refractive Elements	398
16.2.3	Diffraction Elements	399
16.2.4	Variable and Scanning Slit Apertures	400
16.3	Combining Lateral and Hyperspectral Imaging	401
16.4	Lateral Imaging Unit	402
16.5	Spectral Imaging Unit	405
16.5.1	Variable and Scanning Slit Aperture	405
16.5.2	Switchable Grating	408
16.6	System Evaluation	411
16.6.1	Demonstrator Setup	411
16.6.2	Results	412
16.7	Conclusion	413
	References	414
17	Plenoptic Cameras	417
	Andreas Tünnermann, Sylvia Gebhardt, and Henning Fouckhardt	
17.1	History of Light Field Capturing	417
17.2	Adaptive Plenoptic Imaging Systems	419
17.2.1	Preliminary Consideration	419
17.2.2	Light Field Camera with Actuated Imaging Microlens Array	420
17.3	Screen Printed Piezoelectric Actuators	423
17.3.1	Piezoceramic Thick Film Technology	424
17.3.2	Through-Thickness and In-Plane Excitation	425
17.3.3	Actuator Design	425
17.3.4	Actuator Performance	426
17.3.5	Monolithic Actuator Platform	427

17.4	Actuated Micro-iris Array	429
17.4.1	Preliminary Consideration	429
17.4.2	Iris Arrays in Plenoptic Cameras	431
17.5	Conclusion	435
	References	435
	<i>Index</i>	439

Contributors

Chapter 1

Hans Zappe

Department of Microsystems Engineering, University of Freiburg, Germany

Chapter 2

Robert Brunner

Applied Optics, Ernst Abbe University of Applied Sciences, Jena, Germany

Erik Förster

Applied Optics, Ernst Abbe University of Applied Sciences, Jena, Germany

Chapter 3

Wolfgang Mönch

Technische Hochschule Nürnberg Georg Simon Ohm, Nürnberg, Germany

Chapter 4

David Dickensheets

Department of Electrical and Computer Engineering, Montana State University,
Bozeman, MT, USA

Chapter 5

Yen-Sheng Lu

Institute of Electronics Engineering, National Tsing Hua University, Taiwan

J. Andrew Yeh

Institute of Nanoengineering and Microsystems, National Tsing Hua University,
Taiwan

Chapter 6

Philipp Müller

Department of Microsystems Engineering, University of Freiburg, Germany

Chapter 7**Peter Liebetraut**

Department of Microsystems Engineering, University of Freiburg, Germany

Sebastian Petsch

Department of Microsystems Engineering, University of Freiburg, Germany

Hans Zappe

Department of Microsystems Engineering, University of Freiburg, Germany

Chapter 8**Michael Jetter**

Institut für Halbleiteroptik und Funktionelle Grenzflächen, Universität Stuttgart, Germany

Peter Michler

Institut für Halbleiteroptik und Funktionelle Grenzflächen, Universität Stuttgart, Germany

Wolfgang Osten

Institut für Technische Optik, Universität Stuttgart, Germany

Michael Rutloh

Universität Potsdam, Germany

Frederik Schaal

Institut für Technische Optik, Universität Stuttgart, Germany

Joachim Stumpe

Fraunhofer IAP, Universität Potsdam, Germany

Susanne Weidenfeld

Institut für Halbleiteroptik und Funktionelle Grenzflächen, Universität Stuttgart, Germany

Chapter 9**Oliver Ambacher**

Fraunhofer Institute for Applied Solid State Physics, and Department of Microsystems Engineering, University of Freiburg, Freiburg, Germany

Martin Hoffmann

Technische Universität Ilmenau, Fachgebiet Mikromechanische Systeme, Ilmenau, Germany

Fabian Knöbber

Fraunhofer Institute for Applied Solid State Physics, and Department of Microsystems Engineering, University of Freiburg, Freiburg, Germany

Vadim Lebedev

Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany

Contributors

xix

Steffen Leopold

Technische Universität Ilmenau, Fachgebiet Mikromechanische Systeme, Ilmenau, Germany

Daniel Pätz

Technische Universität Ilmenau, Fachgebiet Technische Optik, Ilmenau, Germany

Stefan Sinzinger

Technische Universität Ilmenau, Fachgebiet Technische Optik, Ilmenau, Germany

Verena Zürbig

Fraunhofer Institute for Applied Solid State Physics, and Department of Microsystems Engineering, University of Freiburg, Freiburg, Germany

Chapter 10**Jan Draheim**

Department of Microsystems Engineering, University of Freiburg, Germany

Ulrike Wallrabe

Department of Microsystems Engineering, University of Freiburg, Germany

Chapter 11**Heidi Ottevaere**

Department of Applied Physics and Photonics, Vrije Universiteit Brussel, Brussels, Belgium

Lien Smeesters

Department of Applied Physics and Photonics, Vrije Universiteit Brussel, Brussels, Belgium

Hugo Thienpont

Department of Applied Physics and Photonics, Vrije Universiteit Brussel, Brussels, Belgium

Chapter 12**Olav Solgaard**

Department of Electrical Engineering, Stanford University, USA

Xuan Wu

Department of Electrical Engineering, Stanford University, USA

Chapter 13**Changho Chong**

Santec Corporation, Japan

Keiji Isamoto

Santec Corporation, Japan

Hiroshi Toshiyoshi

Research Center for Advanced Science and Technology, The University of Tokyo,
Japan

Chapter 14**Sebastian Petsch**

Department of Microsystems Engineering, University of Freiburg, Germany

Richard Rix

Institute for Organic Chemistry, University of Mainz, Germany

Stefan Schuhladen

Department of Microsystems Engineering, University of Freiburg, Germany

Hans Zappe

Department of Microsystems Engineering, University of Freiburg, Germany

Rudolf Zentel

Institute for Organic Chemistry, University of Mainz, Germany

Chapter 15**Oliver Ambacher**

Fraunhofer Institute for Applied Solid State Physics, and Department of Microsystems Engineering, University of Freiburg, Freiburg, Germany

Tobias Deutschmann

University of Kaiserslautern, Department of Physics, Kaiserslautern, Germany

Martin Hoffmann

Technische Universität Ilmenau, Fachgebiet Technische Optik, Ilmenau, Germany

Vadim Lebedev

Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany

Steffen Leopold

Technische Universität Ilmenau, Fachgebiet Mikromechanische Systeme, Ilmenau, Germany

Egbert Oesterschulze

University of Kaiserslautern, Department of Physics, Kaiserslautern, Germany

Daniel Pätz

Technische Universität Ilmenau, Fachgebiet Technische Optik, Ilmenau, Germany

Stefan Sinzinger

Technische Universität Ilmenau, Fachgebiet Technische Optik, Ilmenau, Germany

Verena Zürbig

Fraunhofer Institute for Applied Solid State Physics, and Department of Microsystems Engineering, University of Freiburg, Freiburg, Germany

Chapter 16**Mohammad Abdo**

Department of Microsystems Engineering, University of Freiburg, Germany

Kaustubh Banerjee

Department of Microsystems Engineering, University of Freiburg, Germany

Patrick Bohnert

Applied Optics, Ernst Abbe University of Applied Sciences, Jena, Germany

Robert Brunner

Applied Optics, Ernst Abbe University of Applied Sciences, Jena, Germany

Erik Förster

Applied Optics, Ernst Abbe University of Applied Sciences, Jena, Germany

Jan G. Korvink

Department of Microsystems Engineering, University of Freiburg, Germany

Benjamin Ryba

Applied Optics, Ernst Abbe University of Applied Sciences, Jena, Germany

Stefan Schuhladen

Department of Microsystems Engineering, University of Freiburg, Germany

Moritz Stürmer

Department of Microsystems Engineering, University of Freiburg, Germany

Ulrike Wallrabe

Department of Microsystems Engineering, University of Freiburg, Germany

Chapter 17**Ben Bockwinkel**

University of Kaiserslautern, Department of Physics, Kaiserslautern, Germany

Bernhard Bramlage

Fraunhofer Institute for Ceramic Technologies and Systems, Dresden, Germany

Dörthe Ernst

Fraunhofer Institute for Ceramic Technologies and Systems, Dresden, Germany

Henning Fouckhardt

University of Kaiserslautern, Department of Physics, Kaiserslautern, Germany

Sylvia Gebhardt

Fraunhofer Institute for Ceramic Technologies and Systems, Dresden, Germany

Carina Heisel

University of Kaiserslautern, Department of Physics, Kaiserslautern, Germany

Christina Kimmle

University of Kaiserslautern, Department of Physics, Kaiserslautern, Germany

Alexander Oberdörster

Fraunhofer Institute for Applied Optics and Precision Engineering, Germany

Dominic Palm

University of Kaiserslautern, Department of Physics, Kaiserslautern, Germany

Felix Paries

University of Kaiserslautern, Department of Physics, Kaiserslautern, Germany

Johannes Strassner

University of Kaiserslautern, Department of Physics, Kaiserslautern, Germany

Andreas Tünnermann

Institute of Applied Physics, Abbe Center of Photonics, Friedrich Schiller University
Jena, Germany

Frank Wippermann

Fraunhofer Institute for Applied Optics and Precision Engineering, Germany

Acronyms

2D	two-dimensional
3D	three-dimensional
AA	acrylic acid
AC	alternating current
AFM	atomic force microscope
AlN	aluminum nitride
AOSLO	adaptive optics scanning laser ophthalmoscope
ARC	anti-reflective coating
BHF	buffered hydrofluoric acid
BLU	backlighting unit
BOX	buried oxide
CAD	computer aided design
CASSI	coded aperture snapshot spectral imager
CCD	charged-coupled device
CE	counter electrode
CMOS	complementary metal oxide silicon
CT	computerized tomography
CTE	coefficient of thermal expansion
CTIS	computed tomography imaging spectrometer
CVD	chemical vapor deposition
DBR	distributed Bragg reflector
DC	direct current
DEFOC	defocus
DI	de-ionized (water)
DLL	dielectric liquid lens
DMAEMA	2-dimethylaminoethyl methacrylate
DMD	digital mirror device
DNA	deoxyribonucleic acid
DOE	diffractive optical elements
DOF	depth of field
DRIE	deep reactive ion etching
EAP	electroactive polymer
EC	electrochromic

ECX	equiconvex
EM	electromagnetic
EWOD	electrowetting-on-dielectrics
FIB	focused ion beam
FCC	face centered cubic
FD-OCT	Fourier-domain OCT
FEM	finite element method
FLC	ferroelectric liquid crystal
FOV	field of view
FP	Fabry-Pérot (interferometer)
FWHM	full width at half maximum
GLV	grating light valve
GO-GMA	glycidylmethacrylate-functionalized graphene oxide
GRIN	graded index
HCP	hexagonal close-packed
IC	integrated circuit
IFT	interfacial tension
IHTFP	rude MIT colloquialism
IOL	intra-ocular lens
IPA	isopropyl alcohol
IR	infrared
ITO	indium tin oxide
I2C	inter-integrated circuit
LC	liquid crystal
LCA	longitudinal chromatic aberration
LCD	liquid crystal display
LCE	liquid crystal elastomer
LCOS-SLM	liquid crystal on silicon spatial light modulators
LDV	laser Doppler vibrometry
LED	light emitting diodes
LOC	lab-on-a-chip
LPCVD	low pressure chemical vapor deposition
LTCC	low temperature cofired ceramics
MEMS	micro-electro-mechanical systems
MOVPE	metal-organic vapor-phase epitaxy
MTF	modulation transfer function
MZ	Mach-Zehnder (interferometer)
NA	numerical aperture
NCD	nanocrystalline diamond
NIPAAm	N-isopropylacrylamide
NMR	nuclear magnetic resonance
OASLM	optically addressed spatial light modulators
OCT	optical coherence tomography
OLED	organic light emitting diodes

Acronyms

xxv

OT	optical transmission
OTF	optical transfer function
PAC	photo addressable cell
PBS	polarizing beam splitter
PC	polycarbonate
PCB	printed circuit board
PDMS	polydimethylsiloxane
PEDOT	poly-3, 4-ethylenedioxythiophene
PEEK	polyetheretherketone
PLA	polylactic acid
PMMA	polymethylmethacrylate
PNIPAAm	poly(N-isopropylacrylamide)
PSF	point spread function
PSI	phase shifting interferometry
PV	peak-valley
PZT	lead zirconate titanate
R&D	research and development
RCWA	rigorous coupled wave analysis
RIE	reactive ion etching
RMS	root mean square
ROC	radius of curvature
RPG	resonant periodic gain
SA	spherical aberration
SAM	self-assembled monolayers
SD-OCT	spectral-domain OCT
SEM	scanning electron microscope
SLM	spatial light modulators
SMA	shape-memory alloy
SOA	semiconductor optical amplifier
SOI	silicon-on-insulator
SS-OCT	swept-source OCT
SXGA	super extended graphics array
μ TAS	micro total analysis system
TCL	three-phase contact line
TCO	transparent conductive oxide
TD-OCT	time-domain OCT
TE	transverse electric
TF	tetrafoil
THF	tetrahydrofuran
TM	transverse magnetic
TMAH	tetra-methyl ammonium hydroxide
TOC	thermo-optic coefficient
USB	universal serial bus
UV	ultraviolet

VB	valence band
VASE	variable angle spectral ellipsometry
VCM	voice coil motors
VCSEL	vertical-cavity surface-emitting laser
VOA	variable optical attenuators
VDM	wavelength division multiplex
WE	working electrode
WLI	white light interferometry
WLIM	white light interference microscopy