Fundamentals of Micro-Optics

From optical fundamentals to advanced applications, this comprehensive guide to micro-optics covers all the key areas for those who need an in-depth introduction to micro-optic devices, technologies, and applications. Topics covered range from basic optics, optical materials, refraction, and diffraction, to micromirrors, microlenses, diffractive optics, optoelectronics, and fabrication. Advanced topics, such as tunable and nano-optics, are also discussed. Real-world case studies and numerous worked examples are provided throughout, making complex concepts easier to follow, whilst an extensive bibliography provides a valuable resource for further study. With exercises provided at the end of each chapter to aid and test understanding, this is an ideal textbook for graduate and advanced undergraduate students taking courses in optics, photonics, micro-optics, microsystems, and MEMS. It is also a useful self-study guide for research engineers working on optics development.

Hans Zappe is Professor of Micro-Optics in the Department of Microsystems Engineering at the University of Freiburg, Germany. He has 20 years' experience working on optical micro- and nanosystems, integrated optics, and semiconductor lasers, and he is internationally renowned for his teaching and research. He has previously authored two textbooks, and his current research interests include the use of micro-optics for medical applications and the development of tunable micro-optical components and systems.

"... presents this exciting field of research comprehensively and gives in-depth insight into its key aspects of passive and active micro-optics ... an exciting and inspiring read for anyone in this field of research, written by one of the leading scientists on tunable micro-fluidics... Most felicitous are the very good compromise between compactness, completeness, readability, and clearness, the huge number of exercises with the instructor-only manual, the extensive bibliography, the perspectives for application today and tomorrow, and finally the fascinating application oriented case studies... Graduates, young and senior scientists and engineers will apply this book with enthusiasm and success. Congratulations on this extended volume."

Hartmut Hillmer, Universität Kassel

"...an excellent and comprehensive overview of the science and practice of miniaturized optical systems... The comprehensive coverage, thoughtful explanations, and many well-chosen examples and problems make this an excellent text for a course on the fundamentals of micro-optics, and its clear and concise style makes it ideal for self-studies."

Olav Solgaard, Stanford University

"...an excellent textbook that offers, within one cover, a broad sampling of micro-optical devices and technologies along with a treatment of the relevant physical fundamentals with sufficient depth to support real engineering. The textbook will be embraced both by students who are seeing these concepts for the first time and by practicing engineers who will find it a useful reference for day-to-day design work. Professor Zappe's style is light and entertaining, but he shows attention to detail and careful notation that students will appreciate. Throughout the work, he shares his passion for the history and context of optical device engineering, and the extensive bibliography is a valuable gateway for further in-depth study."

David Dickensheets, Montana State University

"...a comprehensive summary of an exciting new field by a well-known researcher who has himself made many important contributions. The text is well written and accessible, with many references to real-world examples... The text is up to date, with good coverage of modern themes such as micro-electro-mechanical systems, electrowetting, polymer optoelectronics, quantum dots, plasmonics, and optical metamaterials... The figures and photographs are well chosen, and contain examples from the leading researchers in the field. The illustrative examples and tutorial problems are well thought-out and instructive."

Richard Syms, Imperial College London

Cambridge University Press & Assessment
978-0-521-89542-2 — Fundamentals of Micro-Optics
Hans Zappe
Frontmatter
More Information

Fundamentals of Micro-Optics

HANS ZAPPE
University of Freiburg, Germany

CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

Shaftesbury Road, Cambridge CB2 8EA, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment,
a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of
education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9780521895422

First published 2010

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

Library of Congress Cataloging-in-Publication data
Zappe, Hans P.
Fundamentals of micro-optics /Hans Zappe.
p. cm.
Includes bibliographical references.
ISBN 978-0-521-89542-2 (hardback)
1. Integrated optics. 2. Optical MEMS. 3. Optics.
4. Optical instruments. I. Title.
TA1660.Z366 2010
621.36´93–dc22

2010027365

ISBN 978-0-521-89542-2 Hardback

Additional resources for this publication at www.cambridge.org/9780521895422

On ne peut me connaître
mieux que tu me connais. . .

Contents

Preface — *page* xi
Acknowledgments — xiii
Notation — xv

Part I Essential optics — 1

1 Introduction — 3
1.1 Optics: history in a nutshell — 4
1.2 Micro-optics: a smaller nutshell — 10
1.3 Micro-optics for the home: the DMD — 14

2 The physics of light — 17
2.1 Basic electromagnetics — 17
2.2 Wave propagation — 25
2.3 Electromagnetic waves — 30
2.4 Polarization — 36
2.5 Wavefronts — 40
2.6 Gaussian beams — 46

3 Optical materials — 55
3.1 Refractive index — 56
3.2 Dispersion — 68
3.3 Attenuation — 77
3.4 Glass — 82
3.5 Semiconductors — 86
3.6 Other materials — 93

4 Optical interfaces — 101
4.1 Reflection and refraction — 101
4.2 Reflected and transmitted fields — 106
4.3 Power transmission and reflection — 112
4.4 Internal reflection — 114
4.5 Evanescent field — 119

Cambridge University Press & Assessment
978-0-521-89542-2 — Fundamentals of Micro-Optics
Hans Zappe
Frontmatter
More Information

5 Interferometry 125
5.1 Coherence and interference 125
5.2 Interferometers 135
5.3 Optical multilayers 150

Part II Micro-optics 167

6 Reflective micro-optics 169
6.1 Reflection 169
6.2 Planar mirrors 172
6.3 Nonplanar mirrors 175
6.4 Micromirrors 181
6.5 Adaptive micro-optics 189
6.6 Micromirrors: case studies 193

7 Refractive micro-optics 203
7.1 Lens fundamentals 204
7.2 Imaging 212
7.3 Advanced lenses 225
7.4 Primary aberrations 235
7.5 Chromatic aberrations 244
7.6 Microlenses: case studies 248

8 Diffractive micro-optics 265
8.1 Diffraction 266
8.2 Practical apertures 270
8.3 Gratings 283
8.4 Diffractive microlenses 299
8.5 Diffractive micro-optics: case studies 310

9 Guided-wave micro-optics 321
9.1 Waveguides: ray-optic model 322
9.2 Waveguides: electromagnetic model 337
9.3 Channel waveguides 349
9.4 Waveguide characterization 354
9.5 Waveguide components 363
9.6 Optical fibers 369
9.7 Waveguide micro-optics: case studies 379

10 Active micro-optics 393
10.1 Physics of light emission 393
10.2 Light-emitting diodes 403
10.3 Laser diodes 411

10.4	Photodetectors	428
10.5	Phase and intensity modulators	437
10.6	Other active components	446
10.7	Active micro-optics: case studies	452
11	**Micro-optical fabrication**	463
11.1	Basic semiconductor processing	464
11.2	Self-assembly lenses	466
11.3	Lithography for microlenses	472
11.4	Replication	480
11.5	Specialized processes	485
11.6	Assembly	489
Part III	**Neoteric optics**	499
12	**Tunable micro-optics**	501
12.1	Liquid microlenses	502
12.2	Membrane microlenses	508
12.3	LCD-based tunable micro-optics	514
12.4	Tunable diffractive micro-optics	516
12.5	A tunable micromenagerie	520
13	**Fluidic micro-optics**	523
13.1	Optofluidics	524
13.2	Fluidic waveguides	524
13.3	Optofluidic lasers	525
13.4	Fluidic microlenses	530
13.5	Filters and displays	531
13.6	Other optofluidic concepts	533
14	**Nano-optics**	535
14.1	Nanophotonics	535
14.2	Photonic crystals	537
14.3	Plasmonics	552
14.4	Metamaterials	556
	References	558
	Index	605

Preface

Certains hommes parlent durant leur sommeil. Il n'y a guère que les conférenciers pour parler pendant le sommeil des autres.[1]

Alfred Capus

Microsystems have evolved from laboratory curiosities to pervasive constituents of a colorful spectrum of technical products. We can shake our MP3 players to change the song order; print on square meters of paper at 600 dot per inch resolution; have our doctors perform on-the-spot diagnostics; interact with computer games through our body motions; or have our lives saved by an inflated airbag: all these are possible because a microsystem is embedded somewhere, usually as invisible as it is indispensable.

The micro-electro-mechanical systems that first emerged from university laboratories in the 1980s combined mechanics with the technologies of electronics, leading to the term MEMS. But the technology has expanded enormously since then, so that the microelectronics and micromechanics of the germinal MEMS field now include microfluidics, microacoustics, micromagnetics, microchemistry, microbiology, and, not least, micro-optics. The integration of these disparate disciplines into highly functional microsystems with myriad applications is a key reason for the explosive development of these technologies, and as a result, the essence of much microsystems research is now often highly interdisciplinary.

Of these diverse disciplines, optical microsystems have seen particularly strong development, due primarily to the insatiable demand for communications bandwidth. Long- and medium-range telecommunications networks are almost completely optical, and it is the availability of micro-optical components, such as laser diodes, microlenses, fiber couplers, photodetectors, modulators and optical switches, and their integration into complex communications subsystems, that allows us to convey hundreds of petabytes about the planet... daily.

Micro-optics developed as a branch of classical optics in the latter half of the twentieth century, and focused initially on miniaturized refractive lenses and novel forms of diffractive optics. In recent years it has begun to meld with the capabilities of microsystems such that the fields of micro-optics, optical microsystems, integrated optics, and optical MEMS share many technologies, components, and envisaged applications. Thus

[1] "Some people talk in their sleep. Lecturers talk while other people sleep." Alfred Capus (1857–1922), French journalist and playright.

if we consider “micro-optics” in this text, we do so in the context of numerous other overlapping disciplines, and realize that the field is now much more than microscopic lenses and clever holograms.

As a result, whereas optical telecommunications continues to provide considerable impetus for further development of optical microsystems, the range of micro-optical applications has expanded significantly. Beyond the laser-based reader heads used in conventional optical data storage, and the micromirror arrays on which many beamers rely, micro-optics is found in systems ranging from clinical instrumentation, including intra-corporal imaging and advanced optical medical diagnostics, to advanced scientific imaging concepts, with which astronomers use MEMS-based adaptive optical mirrors for wavefront correction to compensate for atmospheric distortion. As an increasing spectrum of industrial manufacturers becomes aware of the capabilities of micro-optics, the applications spectrum will likewise grow.

We therefore address the varied aspects of the micro-optics field in the text that follows, and run the gamut from the basics of classical optics to advances in nanophotonics. The scope is wide, but the focus is on the engineering of micro-optics: the reader should feel confident in the analysis or design of a micro-optical component or system after ploughing through the text. If, in addition, a fascination with photons ensues, I will have the same feeling of success as I do after holding an optics lecture in which no one audibly snored.

Freiburg and Zurich, January 2010

Cambridge University Press & Assessment
978-0-521-89542-2 — Fundamentals of Micro-Optics
Hans Zappe
Frontmatter
More Information

Acknowledgments

That this text saw completion is due in no small part to contributions from a great many people, all with better things to do than provide me with materials, pictures, data, or information. It is with sincere gratitude that I acknowledge the selfless support of the many students, senior scientists, colleagues, and random victims who happened to be in the lab at the wrong time who all cheerfully lent me a hand.

I am particularly grateful to many present and past members of the Laboratory for Micro-optics in the Department of Microsystems Engineering at the University of Freiburg for their unwavering support, and also to many of my past students for their contributions. Thanks are due to Bernd Aatz for the fringes of Chapters 5, 7, and 8, and all the ZEMAX simulations in Chapter 7; to Stefan Reichelt, now at SeeReal Technologies, Dresden (D), for the lens profiles in Chapter 5; to Khaled Aljasem and Andreas Fischer, the latter now at Chalmers University of Technology, Göteborg (S), for the micromirror photos of Chapter 6; to David Kallweit, now at the Fraunhofer Institute for Photonic Microsystems, Dresden (D), for his mirror pictures in Chapter 6 and grating structures of Chapter 8; to Armin Werber, now at Carl Zeiss SMT, Oberkochen (D), for all the pneumatics and balloon pictures in Chapter 6, the pneumatic microlens process of Chapter 11, and the membrane microlens diagrams and photos of Chapter 12; to Christoph Friese, now at Robert Bosch in Reutlingen (D), for his SU-8 adaptive optical mirrors, presented in Chapter 6; to Fabian Zimmer, now at the Fraunhofer Institute for Photonic Microsystems, Dresden (D), for the polymer lens profile in Chapter 7; to Andreas Mohr, now at the Fraunhofer Institute for Solar Energy Systems, Freiburg (D), for the embossed Fresnel lens in Chapter 7; to Daniel Hofstetter, now at the Université de Neuchâtel (CH), for the DBR grating photograph of Chapter 8, the Michelson interferometer displacement sensor presented in Chapter 9, and the photograph of the quantum cascade laser of Chapter 10; to Eva Geerlings, now at Sick AG, Waldkirch (D), and her colleagues at the Fraunhofer Institute for Applied Solid State Physics, Freiburg (D), for the photos of the external cavity structure of Chapter 8; to Dennis Hohlfeld, now at the Holst Center of IMEC, Eindhoven (NL), for the thermo-optic filter photograph of Chapter 8, and the silicon optical bench with fibers in Chapter 11; to Bernd Maisenhölder, now at Oerlikon Balzers (CH), for the Mach–Zehnder-based refractive index sensor of Chapter 9; to Robert Gehrke for the LED photograph and spectra of Chapter 10; to Jens Fiala and Niklas Weber for the photograph of the implantable pulse oxymeter in Chapter 10; to Daniel Mader for the photos of the molded PDMS micro-optical/microfluidic structures in Chapter 11 and the multi-chamber microlens picture of Chapter 12; to Holger Krause, now working on oil platforms off the coast of Nigeria, for the sol-gel lens photos of Chapter 11; to Wolfgang Mönch for the photoresist reflow lens pictures of Chapter 11; to Michael Engler, who now has his own optical design company, for the mold and injection-molded Fresnel lens of Chapter 11; to Florian Krogmann, now at IST AG, Wattwil (CH), for the silicon optical bench of Chapter 11 and the liquid microlens pictures of Chapter 12; to Thorsten Faber, now at the Fraunhofer Institute for the Mechanics of Materials, Freiburg (D), for the actuated liquid lenses of Chapter 12; to Ryaz Pasha Shaik for the two-dimensional repositionable liquid lens of Chapter 12; to Khaled Aljasem and Wei Zhang for the membrane lens data of Chapter 12; and to Christoph Schlägl and Yaxiu Sun for the bandgap calculations and 2D photonic crystal photos of Chapter 14.

In addition, I am most indebted to Wolfgang Mönch, Andreas Seifert, Daniel Mader, Philipp Waibel, Philipp Müller, and Yaxiu Sun for reading through portions of the manuscript and providing corrections and useful comments. Additional and repeated thanks go to Daniel Mader for putting up with inane LaTeX questions; to Simon Dreher for writing the LaTeX routine that allows the citations at the start of each chapter; to Philipp Waibel for compensating for my inadequacies in *Mathematica*; to Claudia Duppé for taming my propensity for excessive hyphenation; and to Nadja Katthagen for keeping the wolves at bay when I needed a few hours without someone desperately clamoring for the Dean's opinion or signature on something.

I also extend warm thanks to friends and colleagues distributed about the globe for their generous contributions of photos and figures representing some cutting-edge work in micro-optics. Thank you to Markus Rossi of Heptagon Oy (SF and CH) for the Fresnel-like diffractive lens and the DOE of Chapter 8; to Oliver Ambacher and Wolfgang Bronner of the Fraunhofer Institute for Applied Solid State Physics (D) for the photograph of the OEIC chip in Chapter 9; to Kerry Vahala of Caltech (USA) for the disk laser photograph in Chapter 10; to James Harris of Stanford University (USA) for the SEM of the tunable VCSEL in Chapter 10; to George Whitesides of Harvard University (USA) for the diagrams of his optofluidic dye laser of Chapter 13; to Demetri Psaltis and Wuzhou Song of the EPFL (CH) for the schematics and optical characteristics of their opto-fluidic DFB lasers of Chapter 13; to Jason Heikenfeld and Kaichang Zhou of the University of Cincinnati (USA) for the photos of their electrowetting display of Chapter 13; to Susumu Noda of Kyoto University (JP) for the characteristics and photos of his photonic crystal resonant cavities in Chapter 14; to Martin Wegener of the Karlsruhe Institute of Technology (D) for the photo of his split ring metamaterials in Chapter 14; to Mark Reed of Yale University (USA) for his nanowires in Chapter 14; to Shawn-Yu Lin of the Rensselaer Polytechnic Institute (USA) for his bent photonic crystal waveguides of Chapter 14; to Kent Choquette of the University of Illinois (USA) for the photonic crystal on a VCSEL in Chapter 14; and to Philip Russell of the Max Planck Institute for the Science of Light (D) for his sampler of photonic crystal cross-sections of Chapter 14.

Finally, I extend my appreciation to all the Microsystems Engineering students who provided suggestions and corrections based on preliminary versions of the text used in the *Mikrooptik* and *Optical Microsystems* courses.

Notation

List of symbols

Notes:

- Vector quantities are given in **boldface** type.
- SI units are given except for those cases where non-SI units are traditional.

a	aperture dimension	m
a	spacing between cells (period) of a photonic crystal	m
A	area	m^2
A	aperture function	–
b	aperture dimension	m
$\mathbf{B}$	magnetic flux density	$\mathrm{Wb/m}^2$
BW	bandwidth	Hz
c	speed of light in vacuum	m/s
C	contrast	–
d	spacing or displacement	m
d	penetration depth of evanescent field	m
D	aperture diameter	m
D	dispersion parameter	$\mathrm{ps/km \cdot nm}$
D_M	fiber dispersion due to the material	$\mathrm{ps/km \cdot nm}$
D_T	total fiber dispersion	$\mathrm{ps/km \cdot nm}$
D_{WG}	fiber dispersion due to the waveguide	$\mathrm{ps/km \cdot nm}$
$\mathbf{D}$	electric flux density	$\mathrm{C/m}^2$
E	electric field (scalar)	V/m
$\mathbf{E}$	electric field (vector)	V/m
E	energy	J
E_a	electric field at a given point in an aperture	V/m
E_B	electric field of backward propagating wave	V/m
$\mathrm{E_c}$	conduction band energy	eV
E_C	electric field due to diffraction from a circular aperture	V/m
E_D	electric field due to diffraction from dual slits	V/m
E_F	electric field of forward propagating wave	V/m
$\mathrm{E_g}$	energy gap	eV

E_i	electric field at a given point in an image	V/m
E_i	electric field incident on an interface	V/m
E_N	electric field due to diffraction from N slits	V/m
E_r	electric field reflected from an interface	V/m
E_R	electric field due to diffraction from a rectangular aperture	V/m
E_S	electric field due to diffraction from a 1D slit	V/m
E_t	electric field transmitted through an interface	V/m
$\mathrm{E_v}$	valence band energy	eV
$E_x(y)$	x-directed electric field in a waveguide	V/m
E_0	magnitude of electric field	V/m
E_0'	electric field pre-factor for diffraction integrals	V/m^2
f	focal length	m
f_C	focal length for red wavelengths	m
f_d	focal length of the diffractive part of a hybrid lens	m
f_F	focal length for blue wavelengths	m
f_i	focal length inside a medium, or on image side of lens	m
f_o	focal length on object side of lens	m
f_r	focal length of the refractive part of a hybrid lens	m
f_0	focal length outside a medium	m
F	force	N
F	finesse	–
F_{FK}	Franz–Keldysh coefficient	m^2/V^2
F_i	transmission matrix for thin film i	–
$f/\#$	f-number (of a lens)	–
g	circular aperture radius	m
$g(\nu)$	lineshape function	Hz^{-1}
h	Planck's constant	Js
h	height of the source of a ray above the optical axis	m
h	half of the waveguide core thickness	m
$\mathbf{H}$	magnetic field (vector)	A/m
H_i	magnetic field incident on an interface	A/m
H_r	magnetic field reflected from an interface	A/m
H_t	magnetic field transmitted through an interface	A/m
I	current	A
I	optical intensity	W/m^2
I_d	photodetector dark current	A
I_{max}	maximum optical intensity	W/m^2
I_{min}	minimum optical intensity	W/m^2
I_s	photodetector signal current	A
$I(z)$	optical intensity as function of position	W/m^2
$I(\nu)$	optical intensity as function of frequency	W/m^2
I'	optical power	W
$\mathbf{J}$	current density	A/m^2

Cambridge University Press & Assessment
978-0-521-89542-2 — Fundamentals of Micro-Optics
Hans Zappe
Frontmatter
More Information

k	propagation constant	m^{-1}
$\mathbf{k}$	wavevector	m^{-1}
k_B	Boltzmann constant	J/K
k_I	imaginary part of the wavevector	m^{-1}
k_r	radial propagation constant (for diffraction)	m^{-1}
k_R	real part of the wavevector	m^{-1}
k_x	x-directed propagation constant	m^{-1}
k_{xg}	x-directed propagation constant inside waveguide core	m^{-1}
k_{xL}	x-directed propagation constant in lateral evanescent field	m^{-1}
k_y	y-directed propagation constant	m^{-1}
k_{yc}	y-directed propagation constant in waveguide cap	m^{-1}
k_{yg}	y-directed propagation constant in waveguide core	m^{-1}
k_{ys}	y-directed propagation constant in waveguide substrate	m^{-1}
k_z	z-directed propagation constant	m^{-1}
$\mathbf{k}_0$	wavevector in free space	m^{-1}
k_0	propagation constant in free space	m^{-1}
K	spring constant	N/m
L	length	m
L_c	coherence length	m
L_C	overlap length in a waveguide coupler	m
L_{opt}	optical path length	m
L_x	lateral waveguide curve transition distance	m
L_z	axial waveguide curve transition distance	m
L_π	coupling length for waveguide proximity coupler	m
m	mass	kg
m	azimuthal index of Zernike polynomial	–
m	diffraction order	–
m	zone number in a diffractive Fresnel-like lens	–
m	waveguide mode number	–
m_e	electron mass	kg
m'	waveguide mode number for a mirror waveguide	–
m^*	electron effective mass	kg
M	magnification (for a Gaussian beam)	–
M_T	transverse magnification	–
$M_{T(C)}$	transverse magnification for red wavelengths	–
$M_{T(F)}$	transverse magnification for blue wavelengths	–
$\mathbf{M}$	magnetization	$\mathrm{Wb/m}^2$
n	refractive index	–
n	maximum order of Zernike polynomial	–
n	carrier concentration	cm^{-3}
n_A	refractive index of ambient in liquid lens systems	–
n_c	refractive index of waveguide cap material	–
n_c	refractive index of fiber cladding material	–

n_c	electron density in the conduction band	cm^{-3}
n_C	refractive index at Fraunhofer C-line	–
$n_{cladding}$	refractive index of the waveguide cladding material	–
n_{core}	refractive index of the waveguide core material	–
n_d	refractive index at Fraunhofer d-line	–
n_e	extraordinary refractive index	–
n_e	refractive index at Fraunhofer e-line	–
n_e	electron density	cm^{-3}
n_F	refractive index at Fraunhofer F-line	–
n_g	refractive index of waveguide or fiber core material	–
n_i	refractive index, incident side of interface	–
n_L	refractive index inside a lens	–
n_o	ordinary refractive index	–
n_s	refractive index of waveguide substrate material	–
n_t	refractive index, transmitted side of interface	–
n_v	electron density in the valence band	cm^{-3}
n_0	refractive index outside a lens	–
N	waveguide effective index	–
N	number (of atoms, spots, . . .)	–
NA	numerical aperture	–
NA_{wg}	numerical aperture of a waveguide facet	–
NEP	noise-equivalent power	W
N_i	number of illuminated grating periods	–
N_n^m	normalization factor for Zernike polynomial	–
$\mathbf{P}$	polarization	$\mathrm{C/m}^2$
P	number of phase levels in binary optics	–
P_d	dark power (in a photodetector)	W
P_{opt}	input optical power (in a photodetector)	W
Q	charge	C
Q	quality factor	–
r	distance	m
r	reflectivity	–
r	linear electro-optic (Pockels) coefficient	m/V
$\mathbf{r}$	3D spatial vector	m
$\mathbf{r}$	contour vector (for a contour integral)	m
r_a	aperture radial dimension	m
r_{Airy}	radius of Airy disk	m
r_i	image radial dimension	m
r_g	fiber core radius	m
r_{TE}	TE reflection coefficient	–
r_{TM}	TM reflection coefficient	–
r_0	radius	m
R	reflectance	–

Cambridge University Press & Assessment
978-0-521-89542-2 — Fundamentals of Micro-Optics
Hans Zappe
Frontmatter
More Information

R	radius of curvature	m
R	aperture / image spacing, for diffraction	m
R	spectrometer resolution	–
R	responsivity	A/W
R_L	Gaussian beam radius of curvature, left (input)	m
R_n^m	radial function of Zernike polynomial	–
R_R	Gaussian beam radius of curvature, right (output)	m
$R(z)$	Gaussian beam radius of curvature	m
R_1	radius of curvature of left lens surface	m
R_2	radius of curvature of right lens surface	m
s	sag height (of a lens)	m
s	quadratic electro-optical (Kerr) coefficient	$\mathrm{m^2/V^2}$
$\mathbf{S}$	surface vector (for a surface integral)	$\mathrm{m^2}$
$\mathbf{S}$	Poynting vector (for energy transfer)	$\mathrm{W/m^2}$
S	scalar power density	$\mathrm{W/m^2}$
S	scale factor for microlens size	–
S_{GH}	Goos–Hänchen shift	m
S_i	spacing between lens and image	m
S/N	signal-to-noise ratio	–
S_o	spacing between lens and object	m
t	time	s
t	transmittivity	–
t	waveguide core thickness	m
t_c	coherence time	s
t_{max}	maximum thickness of a Fresnel-like diffractive lens	m
t_{PR}	initial photoresist thickness for reflow microlens	m
t_{step}	height of a phase step for a Fresnel-like diffractive lens	m
t_{TE}	TE transmission coefficient	–
t_{TM}	TM transmission coefficient	–
T	period	s
T	temperature	K
T	transmittance	–
v	velocity	m/s
v_g	group velocity	m/s
v_p	phase velocity	m/s
V	Abbe number	–
V	volume	$\mathrm{m^{-3}}$
V	visibility	–
V	Verdet constant (magneto-optics)	rad/Tm
V_π	modulator voltage required for phase shift of π	V
V_{cyl}	volume of a photoresist cylinder before microlens reflow	$\mathrm{m^3}$
V_{hemi}	volume of a hemispherical microlens after reflow	$\mathrm{m^3}$
w	width	m

Cambridge University Press & Assessment
978-0-521-89542-2 — Fundamentals of Micro-Optics
Hans Zappe
Frontmatter
More Information

w_x	width in the $\mathbf{x}$ direction	m
w_y	width in the $\mathbf{y}$ direction	m
W_E	electric energy density	$\mathrm{J/m^3}$
W_H	magnetic energy density	$\mathrm{J/m^3}$
$W(z)$	Gaussian beam (half-) width	m
W_0	Gaussian beam waist (half-) width	m
W_{0L}	Gaussian beam waist (half-) width at left (input)	m
W_{0R}	Gaussian beam waist (half-) width at right (output)	m
x_a	aperture $\mathbf{x}$ dimension (for diffraction)	m
x_i	image $\mathbf{x}$ dimension (for diffraction)	m
y	height of the intersection of a ray with the lens surface	m
y_a	aperture $\mathbf{y}$ dimension (for diffraction)	m
y_i	image $\mathbf{y}$ dimension (for diffraction)	m
y_i	image size	m
y_o	object size	m
z_i	distance between image and focal point	m
z_L	spacing between Gaussian beam waist and lens, left (input)	m
z_o	distance between object and focal point	m
z_0	Rayleigh range (half of depth of focus)	m
z_{0L}	Rayleigh range (half of depth of focus) at left (input)	m
z_{0R}	Rayleigh range (half of depth of focus) at right (output)	m
z_R	spacing between Gaussian beam waist and lens, right (output)	m
Z	impedance	Ω
Z_0	impedance of free space	Ω
Z_n^m	Zernike polynomial	–
α	absorption coefficient	$\mathrm{m^{-1}}$
α	evanescent decay constant	$\mathrm{m^{-1}}$
α	blaze angle (for blazed gratings)	rad
α	thermal coefficient of expansion	$\mathrm{K^{-1}}$
α_{dB}	logarithmic absorption coefficient	dB/m
α_{wg}	waveguide loss	$\mathrm{m^{-1}}$
α_0	residual absorption losses in a laser material	$\mathrm{m^{-1}}$
β	$\mathbf{z}$-directed propagation constant in a waveguide	$\mathrm{m^{-1}}$
β_0	Bragg (resonance) condition in a 1D periodic structure	$\mathrm{m^{-1}}$
β_{1D}	propagation constant for coupled waves in a periodic structure	$\mathrm{m^{-1}}$
γ	damping coefficient	$\mathrm{s^{-1}}$
γ	optical gain	$\mathrm{m^{-1}}$
γ_{th}	threshold gain	$\mathrm{m^{-1}}$
Γ	phase retardation	rad
Γ	confinement factor, for waveguides	–
δ	phase shift between two electric fields	rad

Cambridge University Press & Assessment
978-0-521-89542-2 — Fundamentals of Micro-Optics
Hans Zappe
Frontmatter
More Information

Δr_{min}	optical resolution	m
Δx	spacing between peak and first minimum in an Airy disk	m
$\Delta\beta$	detuning from resonance in a periodic structure	m^{-1}
$\Delta\lambda$	linewidth	m
$\Delta\lambda_{FP}$	free spectral range	m
$\Delta\nu$	linewidth	Hz
$\Delta\nu_{FP}$	free spectral range	Hz
ϵ	dielectric constant	–
ϵ_d	permittivity of a dielectric layer	F/m
ϵ_m	permittivity of a material	F/m
ϵ_0	permittivity of free space	F/m
ζ	dummy variable	–
η	efficiency	–
η	electrowetting parameter	–
η_{abs}	absolute efficiency (of a grating)	–
η_{abs}	relative efficiency (of a grating)	–
θ_c	critical angle	rad
θ_{div}	divergence angle due to diffraction	rad
θ_i	angle of incidence	rad
θ_o	angle of diffraction	rad
θ_{pe}	external polarization (Brewster) angle	rad
θ_{pi}	internal polarization (Brewster) angle	rad
θ_r	angle of reflection	rad
θ_t	angle of transmission	rad
θ_{tilt}	maximum tilt angle of a micromirror	rad
θ_V	contact angle with applied bias	rad
θ_0	contact angle with no applied bias	rad
Θ	polarization rotation angle	rad
κ	coupling coefficient for waveguide proximity coupler	m^{-1}
κ_m	coupling coefficient in coupled wave analysis	m^{-1}
λ	wavelength	m
λ_B	blaze wavelength	m
λ_C	wavelength of Fraunhofer C-line	m
λ_d	wavelength of Fraunhofer d-line	m
λ_e	wavelength of Fraunhofer e-line	m
λ_F	wavelength of Fraunhofer F-line	m
λ_0	wavelength in free space	m
Λ	spatial period (e.g., of a grating)	m
μ	magnetic constant	–
μ_m	permeability of a material	H/m
μ_0	permeability of free space	H/m
ν	frequency	Hz
ν_d	Abbe number based on Fraunhofer d-line	–

ν_D	Abbe number for diffractive lens	–
ν_e	Abbe number based on Fraunhofer e-line	–
ξ	opto-thermal expansion coefficient	K^{-1}
ξ_d	opto-thermal expansion coefficient of a diffractive lens	K^{-1}
ξ_r	opto-thermal expansion coefficient of a refractive lens	K^{-1}
ρ	charge density	$\mathrm{C/m^3}$
σ	conductivity	$\Omega^{-1}\mathrm{m}^{-1}$
σ_{lv}	interfacial energy between liquid and vapor	$\mathrm{J/m^2}$
σ_{sl}	interfacial energy between substrate and liquid	$\mathrm{J/m^2}$
σ_{sv}	interfacial energy between substrate and vapor	$\mathrm{J/m^2}$
τ	lifetime	s
$\upsilon(x)$	step function	–
ϕ	phase	rad
ϕ	tilt of polarization ellipse	rad
$\phi(z)$	Gouy phase shift	rad
$\Phi(x,y)$	phase function of a diffractive lens	rad
$\Phi(\nu)$	optical energy density per volume per frequency	$\mathrm{J/m^3Hz}$
Φ_ν	optical energy density per volume	$\mathrm{J/m^3}$
χ	susceptibility	–
$\psi(x)$	envelope function of Gaussian beam	$\mathrm{V/m}$
$\Psi(x,y)$	phase function of a DOE wrapped to 2π	rad
ω	angular frequency	$\mathrm{rad/s}$
ω_p	plasma frequency	$\mathrm{rad/s}$
ω_0	resonance frequency	$\mathrm{rad/s}$

List of acronyms and abbreviations

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
AFM	atomic force microscope
APS	active pixel sensor
AR	anti-reflection
AWG	arrayed waveguide grating
BBO	barium borate
BD	Blu-ray disc
CA	chromatic aberration
CCD	charge-coupled detector
CD	compact disc
CMOS	complementary metal oxide semiconductor
COC	cyclo-olefin copolymer
CRT	cathode ray tube
CVD	chemical vapor deposition

DBR	distributed Bragg reflector (laser)
DFB	distributed feedback (laser)
DI	de-ionized (water)
DOE	diffractive optical element
DOF	depth of focus
DVD	digital versatile disc
EAP	electroactive polymer
EDFA	erbium-doped fiber amplifier
EWOD	electrowetting-on-dielectrics
FBG	fiber Bragg grating
fcc	face-centered cubic
FOG	fiber-optic gyro
FSR	free spectral range
FT	Fourier transform
FTTH	fiber-to-the-home
FWHM	full width at half-maximum
GaAs	gallium arsenide
GGG	gadolinium gallium garnet
HEBS	high-energy beam sensitive (glass)
HeCd	helium–cadmium
HEMT	high electron mobility transistor
HeNe	helium–neon
HR	high-reflection
IBM	ion beam milling
ITU-T	International Telecommunication Union
InP	indium phosphide
IR	infrared
ITO	indium tin oxide
KDP	KH_2PO_4
KTP	$KTiOPO_4$
LBO	lithium triborate
LCD	liquid crystal display
LED	light-emitting diode
$LiNbO_3$	lithium niobate
LPCVD	low-pressure chemical vapor deposition
LSF	line spread function
LTCC	low-temperature co-fired ceramic
MEH-PPV	poly(2-methoxy-5-(2’ethyl-hexoxy)-1,4-phenylene-vinylene)
MEMS	microelectromechanical systems
μTAS	micro-total-analysis systems
MMI	multimode interference coupler
MOEMS	micro-opto-electromechanical systems
MOS	metal-oxide-semiconductor

Cambridge University Press & Assessment
978-0-521-89542-2 — Fundamentals of Micro-Optics
Hans Zappe
Frontmatter
More Information

MOSFET	metal-oxide-semiconductor field-effect transistor
MOMS	micro-opto-mechanical systems
MSM	metal-semiconductor-metal (photodetector)
MUMPS	multi user MEMS processes
NA	numerical aperture
NEP	noise-equivalent power
NIR	near infrared
OCT	optical coherence tomography
OEIC	optoelectronic integrated circuit
OMEMS	opto-micro-electromechanical systems
OPD	optical path difference
OPL	optical path length
OXC	optical cross-connect
PC	polycarbonate
PCF	photonic crystal fiber
PDMS	polydimethylsiloxane
PDOT	poly(3, 4-ethylene-dioxythiophene)
PECVD	plasma-enhanced chemical vapor deposition
PEDOT	alternative for poly(3, 4-ethylene-dioxythiophene)
PFPE	perfluoropolyether
PIC	photonic integrated circuit
PLC	planar lightwave circuit
PLZT	lead-lanthanum zirconate-titanate
PMMA	poly methyl methacrylate
POF	plastic optical fiber
PPV	poly-(para-phenelyne vinylene)
PS	polystyrene
PSD	position-sensitive detector
PSF	point spread function
PTFE	polytetrafluoroethylene (Teflon©)
QCL	quantum cascade laser
QCSE	quantum-confined Stark effect
RGB	red, green, blue
RIBE	reactive ion beam etching
RIE	reactive ion etching
rms	root mean square
SA	spherical aberration
SEM	scanning electron microscope
SERS	surface-enhanced Raman spectroscopy
SHG	second harmonic generation
SI	Système International
SiOB	silicon optical bench
SLED	superluminescent light-emitting diode

SMD	surface mount device
SMSR	side-mode suppression ratio
SOA	semiconductor optical amplifier
SOI	silicon-on-insulator
SPR	surface plasmon resonance
SRAM	static random access memory
SUMMiT	Sandia ultra-planar multilevel MEMS technology
SXGA	super extended graphics array
TDLAS	tunable diode laser absorption spectroscopy
TE	transverse electric
TEM	transverse electromagnetic
TIR	total internal reflection
TM	transverse magnetic
UV	ultraviolet
VCSEL	vertical-cavity surface-emitting laser
VOA	variable optical attenuator
WDM	wavelength division multiplexing
YAG	yttrium aluminum garnet
YIG	yttrium iron garnet
YVO	yttrium aluminum vanadate