

Field Guide to

Lens Design

Julie Bentley
Craig Olson

SPIE Field Guides
Volume FG27

John E. Greivenkamp, Series Editor

SPIE
PRESS

Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Bentley, Julie (Julie L.)

Field guide to lens design / Julie Bentley, Craig Olson.
pages cm. – (The field guide series)

Includes bibliographical references and index.

ISBN 978-0-8194-9164-0

I. Lenses—Design and construction. I. Olson, Craig 1971-
II. Title.

QC385.B43 2012

681'.423—dc23

2012035700

Published by

SPIE

P.O. Box 10

Bellingham, Washington 98227-0010 USA

Phone: +1.360.676.3290

Fax: +1.360.647.1445

Email: books@spie.org

Web: <http://spie.org>

© 2012 Society of Photo-Optical Instrumentation Engineers (SPIE)

All rights reserved. No part of this publication may be reproduced or distributed in any form or by any means without written permission of the publisher.

The content of this book reflects the work and thought of the author. Every effort has been made to publish reliable and accurate information herein, but the publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon. For the latest updates about this title, please visit the book's page on our website.

Printed in the United States of America.

First printing



Introduction to the Series

Welcome to the *SPIE Field Guides*—a series of publications written directly for the practicing engineer or scientist. Many textbooks and professional reference books cover optical principles and techniques in depth. The aim of the *SPIE Field Guides* is to distill this information, providing readers with a handy desk or briefcase reference that provides basic, essential information about optical principles, techniques, or phenomena, including definitions and descriptions, key equations, illustrations, application examples, design considerations, and additional resources. A significant effort will be made to provide a consistent notation and style between volumes in the series.

Each *SPIE Field Guide* addresses a major field of optical science and technology. The concept of these *Field Guides* is a format-intensive presentation based on figures and equations supplemented by concise explanations. In most cases, this modular approach places a single topic on a page, and provides full coverage of that topic on that page. Highlights, insights, and rules of thumb are displayed in sidebars to the main text. The appendices at the end of each *Field Guide* provide additional information such as related material outside the main scope of the volume, key mathematical relationships, and alternative methods. While complete in their coverage, the concise presentation may not be appropriate for those new to the field.

The *SPIE Field Guides* are intended to be living documents. The modular page-based presentation format allows them to be easily updated and expanded. We are interested in your suggestions for new *Field Guide* topics as well as what material should be added to an individual volume to make these *Field Guides* more useful to you. Please contact us at fieldguides@SPIE.org.

John E. Greivenkamp, *Series Editor*
Optical Sciences Center
The University of Arizona

The Field Guide Series

Keep information at your fingertips with all of the titles in the Field Guide Series:

- Adaptive Optics, Second Edition*, Robert Tyson & Benjamin Frazier
- Atmospheric Optics*, Larry Andrews
- Binoculars and Scopes*, Paul Yoder, Jr. & Daniel Vukobratovich
- Diffraction Optics*, Yakov Soskind
- Geometrical Optics*, John Greivenkamp
- Illumination*, Angelo Arecchi, Tahar Messadi, & John Koshel
- Image Processing*, Khan M. Iftekharuddin & Abdul Awwal
- Infrared Systems, Detectors, and FPAs, Second Edition*, Arnold Daniels
- Interferometric Optical Testing*, Eric Goodwin & Jim Wyant
- Laser Pulse Generation*, Rüdiger Paschotta
- Lasers*, Rüdiger Paschotta
- Microscopy*, Tomasz Tkaczyk
- Optical Fabrication*, Ray Williamson
- Optical Fiber Technology*, Rüdiger Paschotta
- Optical Lithography*, Chris Mack
- Optical Thin Films*, Ronald Willey
- Optomechanical Design and Analysis*, Katie Schwertz & James Burge
- Polarization*, Edward Collett
- Probability, Random Processes, and Random Data Analysis*, Larry Andrews
- Radiometry*, Barbara Grant
- Special Functions for Engineers*, Larry Andrews
- Spectroscopy*, David Ball
- Terahertz Sources, Detectors, and Optics*, Créidhe O'Sullivan & J. Anthony Murphy
- Visual and Ophthalmic Optics*, Jim Schwiegerling

Field Guide to Lens Design

Optical design has a long and storied history, from the magnifiers of antiquity, to the telescopes of Galileo and Newton at the onset of modern science, to the ubiquity of modern advanced optics. The process for designing lenses is often considered both an art and a science. While advancements in the field over the past two centuries have done much to transform it from the former category to the latter, much of the lens design process remains encapsulated in the experience and knowledge of industry veterans. This *Field Guide* provides a working reference for practicing physicists, engineers, and scientists for deciphering the nuances of basic lens design. Because the optical design process is historically (and quite practically) closely related to ray optics, this book is intended as a companion to the *Field Guide to Geometrical Optics*, in which first-order optics, thin lenses, and basic optical systems are treated in more detail. Note that this compact reference is not a substitute for a comprehensive technical library or the experience gained by sitting down and designing lenses.

This material was developed over the course of several years for undergraduate and graduate lens design classes taught at the University of Rochester. It begins with an outline of the general lens design process before delving into aberrations, basic lens design forms, and optimization. An entire section is devoted to techniques for improving lens performance. Sections on tolerancing, stray light, and optical systems are followed by an appendix covering related topics such as optical materials, nonimaging concepts, designing for sampled imaging, and ray tracing fundamentals, among others.

Thanks to both of our families—Danielle, Alison, Ben, Sarah, Julia, and especially our spouses, Jon and Kelly. The cats will now get fed, and all soccer parents beware!

Julie Bentley

University of Rochester

Craig Olson

L-3 Communications

Table of Contents

Glossary of Symbols and Acronyms	xi
Fundamentals of Optical Design	1
Sign Conventions	1
Basic Concepts	2
Optical Design Process	3
Aperture and Wavelength Specifications	4
Resolution and Field of View	5
Packaging and Environment	6
Wave Aberration Function	7
Third-Order Aberration Theory	8
Spot Diagram and Encircled Energy	9
Transverse Ray Plot	10
Wavefront or OPD Plots	11
Point Spread Function and Strehl Ratio	12
MTF Basics	13
Using MTF in Lens Design	14
Defocus	15
Wavefront Tilt	16
Spherical Aberration	17
Coma	18
Field Curvature	19
Petzval Curvature	20
Astigmatism	21
Distortion	22
Primary Color and Secondary Color	23
Lateral Color and Spherochromatism	24
Higher-Order Aberrations	25
Intrinsic and Induced Aberrations	26
Design Forms	27
Selecting a Design Form: Refractive	27
Selecting a Design Form: Reflective	28
Singlets	29
Achromatic Doublets	30
Airspaced Doublets	31
Cooke Triplet	32
Double Gauss	33
Petzval Lens	34
Telephoto Lenses	35
Retrofocus and Wide-Angle Lenses	36
Refractive versus Reflective Systems	37
Obscurations	38
Newtonian and Cassegrain	39

Table of Contents

Gregorian and Schwarzschild	40
Catadioptric Telescope Objectives	41
Unobscured Systems: Aperture Clearance	42
Unobscured Systems: Field Clearance	43
Three-Mirror Anastigmat	44
Reflective Triplet	45
Wide-Field Reflective Design Forms	46
Zoom Lens Fundamentals	47
Zoom Lens Design and Optimization	48
Improving a Design	49
Techniques for Improving an Optical Design	49
Angle of Incidence and Aplanatic Surfaces	50
Splitting and Compounding	51
Diffraction-Limited Performance	52
Thin Lens Layout	53
Lens Bending	54
Material Selection	55
Controlling the Petzval Sum	56
Stop Shift and Stop Symmetry	57
Telecentricity	58
Vignetting	59
Pupil Aberrations	60
Aspheres: Design	61
Aspheres: Fabrication	62
Gradient Index Materials	63
Diffractive Optics	64
Optimization	65
Optimization	65
Damped Least Squares	66
Global Optimization	67
Merit Function Construction	68
Choosing Effective Variables	69
Solves and Pickups	70
Defining Field Points	71
Pupil Sampling	72
Tolerancing	73
Tolerancing	73
Design Margin and Performance Budgets	74
Optical Prints	75
Radius of Curvature Tolerances	76

Table of Contents

Surface Irregularity	77
Center Thickness and Wedge Tolerances	78
Material and Cosmetic Tolerances	79
Lens Assembly Methods	80
Assembly Tolerances	81
Compensators	82
Probability Distributions	83
Sensitivity Analysis	84
Performance Prediction	85
Monte Carlo Analysis	86
Environmental Analysis	87
Athermalization	88
Stray Light	89
Stray Light Analysis	89
Stray Light Reduction	90
Antireflection (AR) Coatings	91
Ghost Analysis	92
Cold Stop and Narcissus	93
Nonsequential Ray Tracing	94
Scattering and BSDF	95
Optical Systems	96
Photographic Lenses: Fundamentals	96
Photographic Lenses: Design Constraints	97
Visual Instruments and the Eye	98
Eyepiece Fundamentals	99
Eyepiece Design Forms	100
Telescopes	101
Microscopes	102
Microscope Objectives	103
Relays	104
Appendix: Optical Fundamentals	105
Index of Refraction and Dispersion	105
Optical Materials: Glasses	106
Optical Materials: Polymers/Plastics	107
Optical Materials: Ultraviolet and Infrared	108
Snell's Law and Ray Tracing	109
Focal Length, Power, and Magnification	110
Aperture Stop and Field Stop	111
Entrance and Exit Pupils	112
Marginal and Chief Rays	113

Table of Contents

Zernike Polynomials	114
Conic Sections	115
Diffraction Gratings	116
Optical Cements and Coatings	117
Detectors: Sampling	118
Detectors: Resolution	119
The Lagrange Invariant and Étendue	120
Illumination Design	121
Equation Summary	122
Bibliography	127
Index	129

Glossary of Symbols and Acronyms

A	Area
AOI	Angle of incidence
AR	Antireflection
BBAR	Broadband antireflection coating
BFL	Back focal length
BFS	Best fit sphere
BRDF	Bidirectional reflectance distribution function
BSDF	Bidirectional scattering distribution function
BTDF	Bidirectional transmittance distribution function
c	Surface curvature
C	Lens conjugate factor
CA	Clear aperture
CCD	Charge-coupled device
CDF	Cumulative distribution function
CGH	Computer-generated hologram
CMOS	Complementary metal-oxide semiconductor
CRA	Chief ray angle
CT	Center thickness
CTE	Coefficient of thermal expansion
CTF	Contrast transfer function
d	Airspace
d	Thickness
DLS	Damped least squares
dn/dT	Thermo-optic coefficient
DOE	Diffraction optical element
EFL	Effective focal length
EPD	Entrance pupil diameter
ESF	Edge-spread function
ETD	Edge thickness difference
f	Focal length
$f/\#$	f -number or relative aperture
FEA	Finite-element analysis

Glossary of Symbols and Acronyms

FFL	Front focal length
FFOV	Full field of view
FFT	Fast Fourier transform
FOV	Field of view
GQ	Gaussian quadrature
GRIN	Gradient index
h, h'	Object/image height
H	Lagrange invariant
H	Normalized field coordinate
HFOV	Half field of view
HO	Higher order
HOE	Holographic optical element
HR	High-reflection
i, i'	Angle of incidence w.r.t. surface normal
i, i_a	Marginal ray angle w.r.t. surface normal
\bar{i}, i_b	Chief ray angle w.r.t. surface normal
ID	Inner diameter of a lens barrel or mount
IR	Infrared
L	Radiance
LOS	Line of sight
LR	Limiting resolution
LSF	Line spread function
LWIR	Long-wave infrared
m	Diffraction order
m	Magnification
MP	Magnifying power (magnifier or telescope)
MTF	Modulation transfer function
MWIR	Midwave infrared
n, n'	Index of refraction
$n(z), n(r)$	Gradient index profile function
NA	Numerical aperture
NITD	Narcissus-induced temperature difference
NRT	Nonsequential ray tracing
NUC	Nonuniformity correction

Glossary of Symbols and Acronyms

OAP	Off-axis parabola
OAR	Off-axis rejection
OD	Outer diameter (of a lens)
OPD	Optical path difference
OTF	Optical transfer function
p	Pixel pitch in sampled detector arrays
P	Partial dispersion
PDF	Probability distribution function
PSF	Point spread function
PSNIT	Point-source normalized irradiance transmittance
PST	Point-source transmittance
P-V	Peak to valley
Q	Sampling ratio
r	Radial surface coordinate
R , ROC	Radius of curvature
RI	Relative illumination
RMS	Root mean square
RSS	Root sum square
RT	Reflective triplet
s, s'	Object/image distance
SA	Spherical aberration
SLR	Single-lens reflex
t	Thickness or airspace
T	Temperature
TIR	Total indicator runout
TIR	Total internal reflection
TIS	Total integrated scatter
TMA	Three-mirror anastigmat
TML	Three mirror long
u, u'	Paraxial ray angles w.r.t. optical axis
u, u_a	Marginal ray angle w.r.t. optical axis
\bar{u}, u_b	Chief ray angle w.r.t. optical axis
UV	Ultraviolet
V	Abbe number
W	Wave aberration function

Glossary of Symbols and Acronyms

W_{ijk}	Wavefront aberration coefficient
WD	Working distance
y, y_a	Marginal ray height at a surface
\bar{y}, y_b	Chief ray height at a surface
z	Optical axis
$z(r)$	Surface sag/profile function
Z_n	Zernike polynomial coefficient
β	Lens shape factor
$\Delta\lambda$	Wavelength range or bandwidth
δz	Defocus
ε	Obscuration ratio
$\varepsilon, \varepsilon_x, \varepsilon_y$	Transverse ray error
θ, θ'	Angle of incidence/refraction
θ	Half field of view
θ	Pupil azimuthal coordinate
κ	Conic constant
λ	Wavelength
λ_0	Center wavelength
ρ, ρ_x, ρ_y	Normalized radial pupil coordinate
Φ	System power
ϕ	Element or surface power
ϕ	Merit or penalty function