

Field Guide to

Optical Fabrication

Ray Williamson

SPIE Field Guides
Volume FG20

John E. Greivenkamp, Series Editor

SPIE
PRESS

Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Williamson, Raymond.

Field guide to optical fabrication / Ray Williamson.

p. cm. -- (The field guide series ; FG20)

Includes bibliographical references and index.

ISBN 978-0-8194-8676-9

1. Optical instruments--Design and construction. 2. Optical instruments--Testing. I. Title.

TS513.W55 2011

681'.4--dc23

2011018206

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>

Copyright © 2011 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:

Field Guide to

Adaptive Optics, Tyson & Frazier

Atmospheric Optics, Andrews

Binoculars and Scopes, Yoder, Jr. & Vukobratovich

Diffraction Optics, Soskind

Geometrical Optics, Greivenkamp

Illumination, Arecchi, Messadi, & Koshel

Infrared Systems, Detectors, and FPAs, Second Edition,
Daniels

Interferometric Optical Testing, Goodwin & Wyant

Laser Fiber Technology, Paschotta

Laser Pulse Generation, Paschotta

Lasers, Paschotta

Microscopy, Tkaczyk

Optical Fabrication, Williamson

Optical Lithography, Mack

Optical Thin Films, Willey

Polarization, Collett

Special Functions for Engineers, Andrews

Spectroscopy, Ball

Visual and Ophthalmic Optics, Schwiegerling

Introduction

Most *Field Guides* address a particular subset of physics and/or mathematics and, as such, can be treated in a linear exposition of theory from first principles. In contrast, optical fabrication consists of a collection of disparate crafts, technologies, and business decisions in the service of making *nearly* perfect physical instances of those geometric and physical theories. I have attempted to organize the subject matter in ways that make sense to me: What the designer needs to know before making final choices, how to specify the components before they are ordered, how conventional fabrication proceeds for representative components, alternative and emerging methods, how the manufacturer plans the work, product evaluation, and calculations used.

This *Field Guide* is intended to serve several audiences, and introduce each to the other. I hope to provide designers and purchasers with some perspectives and appreciation for the craft and business, the shop manager with a concise reference, the optician with a wider overview than one is likely to get within any single company, and the optical community at large with some insight into this fascinating and dynamic enterprise.

Thanks are due to Oliver Föhnle for inputs to synchro speed and fluid jet. I want to particularly acknowledge three influences, true masters in the field: Dick Sumner, Norm Brown, and Frank Cooke. Dick personified excellence in craft, a passionate curiosity, and a focus on effectiveness. Norm brought the light of science and engineering to the hidden mysteries of this once-black art with accessible clarity. Frank was an inspiration to all through his boundless creativity and zest. We are in transition between 20th Century craft and 21st Century technology, and the field will be hardly recognizable in twenty years.

This *Field Guide* is dedicated to my wife, Lore Eargle, in recognition of her encouragement, patience, support, editing, and so much more.

Ray Williamson
August 2011

Table of Contents

Glossary of Symbols and Acronyms	x
Introduction for Designers	1
From Functional Desires to Component Tolerances	1
Clear Aperture	2
Thickness versus Stability and Ease of Fabrication	3
Flatness versus Transmitted Wavefront	4
Scale Factors for Surface and Wavefront	5
Wedge in Nearly Concentric Optics	6
Surface Quality versus Performance	7
“Difficult” and Preferred Materials	8
Pressure-Bearing Window Thickness	9
Specifications Checklist	10
Realistic Tolerances	11
Designing Aspheres for Manufacturability	12
What Kind of Shop Is It?	13
Conventional Fabrication Methods	14
Stages of Conventional Fabrication	14
Shop Safety	15
Blocking Layout	17
Blocking Methods	18
Pitch Pickup Blocking	20
Spot Blocks	21
Wedge Tools	22
Sawing	23
Milling	24
Curve Generating	25
Free-Abrasive Grinding	26
Abrasive Types and Grades	27
Fixed-Abrasive Lapping	28
Beveling	29
Dicing	30
Coring and Drilling	31
Edging	32
Centerless Edging	33
Centering	34
Fractures, Chips, and Stoning	35
Marking: Spot Bevels, Dots, Arrows, etc.	36
Polishing	37
Polishing Compounds	38
Pitch Laps: Channels and Figure Control	39
Polishing Pads	40
Crystal Shaping and Orientation	41

Table of Contents

Crystal Lapping	42
Overarm Spindle Machine	43
Stick Lens Fabrication	44
Planetary Lapping	45
Double-Sided Lapping	46
Cylindrical and Toric Lapping	47
Intrashop Transportation and Storage	48
In-Process Cleaning	49
Cleaning for Thin-Film Coating	50
Thin-Film Coating	51
Assembly	52
Packaging for Shipping	53
Alternative Fabrication Methods	54
CNC with Spindle-Mounted Tools	54
CNC Synchro-speed Polisher	55
CNC Belt Style Machine	56
CNC Bonnet Polisher	57
Magnetorheological Finishing (MRF®)	58
Fluid Jet Polishing (FJP)	59
Single-Point Diamond Turning (SPDT)	60
Replication	61
Plastic Injection Molding	62
Thermoset Casting and Compression Molding	63
Hot Pressing	64
Process-Planning Factors	65
Raw Material and Forms of Supply	65
Starting Material Dimensions	66
Yield from Dicing and Coring	67
Efficient Production and Optimum Quantities	68
Planning for Yield Losses	69
Block Capacity: Flat	70
Wedge Tool Capacity	71
Block Capacity: Radius	72
Scheduling for Coating	73
Directional Inhomogeneity	74
Stresses within Optical Components	75
Stresses Applied to Optical Components	76
Thermal Settling Time	77
Thermal Failure	78
In-Process Inspection Points	79
Dice After Coating?	80
Cements and Adhesives	81

Table of Contents

Evaluation	82
Sampling Inspection and AQL	82
Cosmetic Surface Quality	83
Angle Testing with an Autocollimator	84
Sag and Spherometers	85
Radius, Irregularity, Power, and Figure	86
Interferometry	87
Interferometric Setups	88
PV, RMS, and PVr	89
Fringe Patterns	90
Fringe Scale Factors	91
Conics and Aspheres	92
Dimensional and Geometric Measurement	93
Slope Evaluation Methods	95
Slope Tolerancing	97
 Material Properties	 98
Material Properties of Interest in the Shop	98
Material Properties Table	99
Optical Properties Table	100
Thermal Properties Table	101
Physical Properties Table	102
 Equation Summary	 103
References	110
Bibliography	112
Index	116

Glossary of Symbols and Acronyms

AOI	Angle of incidence
AQL	Acceptance quality level
b	Bevel leg length radial to part diameter
BFS	Best-fit sphere
BK7	Schott glass type 517642
BRDF	Bidirectional reflectance distribution function
C	Curvature, $1/\text{radius}$
$^{\circ}\text{C}$	Degree Celsius
CA	Clear aperture
CGH	Computer-generated hologram
CMM	Coordinate measuring machine
CNC	Computer numerical control
C_p	Specific heat
CT	Center thickness
CTE	Linear coefficient of thermal expansion
D	Diopter, reciprocal meter, unit of focal power
D	Thermal diffusivity
deg	Degree, angular
dn/dT	Change of index with respect to temperature
DPTWF	Double-pass transmitted wavefront
e	Natural logarithm base, ~ 2.718281828
E	Young's modulus
EFL	Effective focal length
ET	Edge thickness
ETV	Edge thickness variation
$^{\circ}\text{F}$	Degree Fahrenheit
FS	Fused silica
GPa	Gigapascals
h	Height of surface form error normal to surface
HF	Hydrofluoric acid
HIP	Hot isostatic pressing
H_K	Knoop hardness
IR	Infrared
K	Kelvin, absolute temperature units
k	Thermal conductivity
mrاد	Milliradian
MRF	Magnetorheological finishing
MSDS	Material safety data sheet
n	Index of refraction

Glossary of Symbols and Acronyms

nm	Nanometer, 10^{-9} m
OPD	Optical path difference
OPL	Optical path length
PSD	Power spectral density
PV	Peak to valley
PVr	Peak to valley, robust (due to C. Evans)
r	Radial distance from axis
R	Radius of curvature
RMS	Root-mean-square
RSS	Root-sum-square
RWF	Reflected wavefront
s	Sag
SCOTS	Software-configurable optical test system
S-D	Scratch-dig (surface quality)
SFE	Surface form error
SPDT	Single-point diamond turning
SQ	Surface quality
SSD	Subsurface damage
t	Thickness
T	Temperature
t_c	Center thickness
t_e	Edge thickness
T_g	Glass transition temperature
TIR	Total internal reflection
TIS	Total integrated scatter
TWD	Transmitted wavefront distortion
TWF	Transmitted wavefront
UV	Ultraviolet
y	Radial distance from axis
z	distance along axis
α	Linear coefficient of thermal expansion
α	Prism angle, wedge, or tilt
α	Angular error from reference, as from 90 deg
δ	Beam deviation
θ_B	Brewster's angle
θ_C	Critical angle
κ	Conic constant
κ	Thermal diffusivity
λ	Wavelength

Glossary of Symbols and Acronyms

μm	micrometer, 10^{-6} m
μrad	Microradian, 10^{-6} rad
ν	Abbé number; reciprocal dispersion
ρ	Specific gravity
σ_f	Rupture strength
τ	Time
ϕ	Diameter
ϕ_{block}	Block diameter
ϕ_{eff}	Effective diameter including spacing