

Field Guide to

Optomechanical Design and Analysis

Katie Schwertz
James H. Burge

SPIE Field Guides
Volume FG26

John E. Greivenkamp, Series Editor

SPIE
PRESS

Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Schwartz, Katie M.

Field guide to optomechanical design and analysis / Katie M. Schwartz, Jim H. Burge.

p. cm. – (The field guide series)

Includes bibliographical references and index.

ISBN 978-0-8194-9161-9

1. Optical instruments—Design and construction—Handbooks, manuals, etc. 2. Optomechanics—Handbooks, manuals, etc. I. Burge, James H. II. Title.

TS513.S385 2012

681'.4—dc23

2012013233

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 © 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*
College of Optical Sciences
The University of Arizona

Field Guide to Optomechanical Design and Analysis

Optomechanics is a field of mechanics that addresses the specific design challenges associated with optical systems. This *Field Guide* describes how to mount optical components, as well as how to analyze a given design. It is intended for practicing optical and mechanical engineers whose work requires knowledge in both optics and mechanics.

Throughout the text, we describe typical mounting approaches for lenses, mirrors, prisms, and windows; standard hardware and the types of adjustments and stages available to the practicing engineer are also included. Common issues involved with mounting optical components are discussed, including stress, glass strength, thermal effects, vibration, and errors due to motion. A useful collection of material properties for glasses, metals, and adhesives, as well as guidelines for tolerancing optics and machined parts can be found throughout the book.

The structure of the book follows Jim Burge's optomechanics course curriculum at the University of Arizona. We offer our thanks to all those who helped with the book's development and who provided content and input. Much of the subject matter and many of the designs are derived from the work of Paul Yoder and Dan Vukobratovich; their feedback is greatly appreciated.

Katie Schwertz
Edmund Optics®

Jim Burge
College of Optical Sciences
University of Arizona

Table of Contents

List of Symbols and Acronyms	ix
Image Motion and Orientation	1
Optical Effects of Mechanical Motion	1
Lens and Mirror Motion	2
Plane Parallel Plate	3
General Image-Motion Equations	4
Image Motion Example	5
Rigid Body Rotation	6
Quantifying Pointing Error	7
Image Orientation	8
Mirror Matrices	10
Mirror Rotation Matrices	12
Cone Intersecting a Plane	13
Stress, Strain, and Material Strength	14
Stress and Strain	14
Strain-vs-Stress Curve	16
Safety Factor	17
Glass Strength	18
Stress Birefringence	20
Precision Positioning	22
Kinematic Constraint	22
Example Constraints and Degrees of Freedom	23
Semi-Kinematic Design	24
Issues with Point Contacts	25
Precision Motion	27
Stage Terminology	28
Linear Stages	29
Rotation and Tilt Stages	30
Errors in Stage Motion	31
Precision Fastening and Adjustments	32
Standard Hardware	32
Example Screws	33
Fastener Strength	34
Tightening Torque	36
Adjusters	37
Differential Screws and Shims	38
Liquid Pinning	39
Electronic Drivers	40
Flexures	41
Stiffness Relations for Single-Strip Flexures	42

Table of Contents

Parallel Leaf Strip Flexures	43
Stiffness Relations for Parallel Leaf Strip Flexures	44
Notch Hinge Flexures	45
Adhesives	46
Adhesive Properties	47
Adhesive Thickness and Shape Factor	48
Thermal Stress	49
Choice of Bond Size and Thickness	50
Mounting of Optical Components	51
Lens Mounts: Off the Shelf	51
Lens Mounting: Custom	53
Calculating Torque and Clearance	54
Potting a Lens with Adhesive	55
Clamped Flange Mount	56
Lens Barrel Assemblies	57
Lens Barrel Assembly Types	58
Surface–Contact Interfaces	60
Prism Types	62
Image-Rotation Prisms	64
Image-Erection Prisms	65
Prism and Beamsplitter Mounting	66
Thin-Wedge Systems	68
Window Mounting	69
Domes	72
Dome Strength	73
Small-Mirror Mounts: Off the Shelf	74
Small-Mirror Mounts: Adhesives and Clamping	75
Small-Mirror Mounts: Tangent Flexure and Hub	76
Mirror Substrates	77
Mirror Substrate Examples	79
Large-Mirror Mounting: Lateral Supports	80
Large-Mirror Mounting: Point Supports	81
Large-Mirror Mounting: Active Supports	82
Self-Weight Deflection: General	83
Self-Weight Deflection: Thin Plates	84
Self-Weight Deflection: Parametric Model	85
Lightweighting Mirrors	86
Flexural Rigidity of Lightweighted Mirrors	88

Table of Contents

Design Considerations and Analysis	89
RMS, P–V, and Slope Specifications	89
Finite Element Analysis	90
Vibration	94
Damping Factor	95
Isolation	96
System Acceleration and Displacement	97
Thermal Effects	98
Heat Flow	100
Air Index of Refraction	102
Athermalization	103
Passive Athermalization	104
Active Athermalization	105
Determining Thermally Induced Stress	106
Alignment	107
Optical and Mechanical Axis of a Lens	108
Alignment Tools	109
Tolerancing	110
Geometric Dimensioning and Tolerancing	110
GD&T Terminology	111
GD&T Symbolology	112
ISO 10110 Standard	113
Appendices	114
Tolerance Guides	114
Clean-Room Classifications	117
Shipping Environments: Vibration	119
Shipping Environments: Drop Heights	120
Unit Conversions	121
Cost and Performance Tradeoffs for Linear Stages	122
Torque Charts	125
Adhesive Properties	127
Glass Properties	130
Metal Properties	134
Equation Summary	136
Glossary	141
Bibliography	144
References	148
Index	149

List of Symbols and Acronyms

%TMC	Percent total mass lost
%CVCM	Percent collected volatile condensable material
a	Acceleration
A	Area
CAD	Computer-aided design
COTS	Commercial off-the-shelf
C_p	Specific heat capacity
CTE	Coefficient of thermal expansion
CVD	Chemical vapor deposition
d	Displacement
d	Distance
D	Diameter
D	Thermal diffusivity
D	flexural rigidity
E	Young's modulus
f	Focal length
F	Force, load
f_0	Natural frequency (Hz)
FEA	Finite element analysis
FEM	Finite element method
g	Gravity (9.8 m/s ²)
G	Shear modulus
GD&T	Geometric dimensioning and tolerancing
h	Height, thickness
IR	Infrared
k	Stiffness
K	Bulk modulus
K_c	Fracture toughness
K_s	Stress optic coefficient
l	Length
L	Length
LMC	Least material condition
LOS	Line of sight
m	Magnification
m	Mass
MMC	Maximum material condition
MoS	Margin of safety
n	Index of refraction
NA	Numerical aperture
NIST	National Institute of Standards and Technology

List of Symbols and Acronyms

OPD	Optical path difference
P	Preload
p	Pressure
PEL	Precision elastic limit
ppm	Parts per million (1×10^{-6})
PSD	Power spectral density
psi	Pounds per square inch
P-V	Peak to valley
Q	Heat flux
r	Radius (distance, i.e., $0.5D$)
R	Radius (of curvature)
RSS	Root sum square
RTV	Room-temperature vulcanization
t	Thickness
T	Temperature
UTS	Unified thread standard
UV	Ultraviolet
x, y, z	Distances in the $x, y,$ or z axis
α	Coefficient of thermal expansion
β	Therm-optic coefficient (coefficient of thermal defocus)
γ	Shear strain
δ	Deflection
ΔT	Change in temperature
Δx	Change in lateral distance (x axis)
Δy	Change in lateral distance (y axis)
Δz	Change in axial distance
ϵ	Emissivity
ε	Strain
ζ	Damping factor
θ	Angle
λ	Thermal conductivity
ν	Poisson ratio
ρ	Density
σ	Stress
σ_{ys}	Yield strength
τ	Shear stress
ω	Frequency
ω_0	Natural frequency (rad/s)