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](mailto: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
- Lens and Mirror Motion
- Plane Parallel Plate
- General Image-Motion Equations
- Image Motion Example
- Rigid Body Rotation
- Quantifying Pointing Error
- Image Orientation
- Mirror Matrices
- Mirror Rotation Matrices
- Cone Intersecting a Plane

## Stress, Strain, and Material Strength
14
- Stress and Strain
- Strain-vs-Stress Curve
- Safety Factor
- Glass Strength
- Stress Birefringence

## Precision Positioning
22
- Kinematic Constraint
- Example Constraints and Degrees of Freedom
- Semi-Kinematic Design
- Issues with Point Contacts
- Precision Motion
- Stage Terminology
- Linear Stages
- Rotation and Tilt Stages
- Errors in Stage Motion

## Precision Fastening and Adjustments
32
- Standard Hardware
- Example Screws
- Fastener Strength
- Tightening Torque
- Adjusters
- Differential Screws and Shims
- Liquid Pinning
- Electronic Drivers
- Flexures
- Stiffness Relations for Single-Strip Flexures
# 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 Symbology 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

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

OPD Optical path difference

$P$ Preload

$p$ Pressure

PEL Precision elastic limit

ppm Parts per million ($1 \times 10^{-6}$)

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

$\alpha$ Coefficient of thermal expansion

$\beta$ Therm-optic coefficient (coefficient of thermal defocus)

$\gamma$ Shear strain

$\delta$ Deflection

$\Delta T$ Change in temperature

$\Delta x$ Change in lateral distance ($x$ axis)

$\Delta y$ Change in lateral distance ($y$ axis)

$\Delta z$ Change in axial distance

$\epsilon$ Emissivity

$\varepsilon$ Strain

$\zeta$ Damping factor

$\theta$ Angle

$\lambda$ Thermal conductivity

$\nu$ Poisson ratio

$\rho$ Density

$\sigma$ Stress

$\sigma_{ys}$ Yield strength

$\tau$ Shear stress

$\omega$ Frequency

$\omega_0$ Natural frequency (rad/s)