Medical Photonics Lecture
Optical Engineering

Lecture 11: Optical Design
2018-01-18
Herbert Gross
<table>
<thead>
<tr>
<th>No</th>
<th>Subject</th>
<th>Ref</th>
<th>Date</th>
<th>Detailed Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>Gross</td>
<td>19.10.</td>
<td>Materials, dispersion, ray picture, geometrical approach, paraxial approximation</td>
</tr>
<tr>
<td>2</td>
<td>Geometrical optics</td>
<td>Gross</td>
<td>02.11.</td>
<td>Ray tracing, matrix approach, aberrations, imaging, Lagrange invariant</td>
</tr>
<tr>
<td>3</td>
<td>Diffraction</td>
<td>Gross</td>
<td>09.11.</td>
<td>Basic phenomena, wave optics, interference, diffraction calculation, point spread function, transfer function</td>
</tr>
<tr>
<td>4</td>
<td>Components</td>
<td>Kempe</td>
<td>16.11.</td>
<td>Lenses, micro-optics, mirrors, prisms, gratings</td>
</tr>
<tr>
<td>5</td>
<td>Optical systems</td>
<td>Gross</td>
<td>23.11.</td>
<td>Field, aperture, pupil, magnification, infinity cases, lens makers formula, etendue, vignetting</td>
</tr>
<tr>
<td>6</td>
<td>Aberrations</td>
<td>Gross</td>
<td>30.11.</td>
<td>Introduction, primary aberrations, miscellaneous</td>
</tr>
<tr>
<td>7</td>
<td>Image quality</td>
<td>Gross</td>
<td>07.12.</td>
<td>Spot, ray aberration curves, PSF and MTF, criteria</td>
</tr>
<tr>
<td>8</td>
<td>Instruments I</td>
<td>Kempe</td>
<td>14.12.</td>
<td>Human eye, loupe, eyepieces, photographic lenses, zoom lenses, telescopes</td>
</tr>
<tr>
<td>9</td>
<td>Instruments II</td>
<td>Kempe</td>
<td>21.12.</td>
<td>Microscopic systems, micro objectives, illumination, scanning microscopes, contrasts</td>
</tr>
<tr>
<td>10</td>
<td>Instruments III</td>
<td>Kempe</td>
<td>11.01.</td>
<td>Medical optical systems, endoscopes, ophthalmic devices, surgical microscopes</td>
</tr>
<tr>
<td>11</td>
<td>Optic design</td>
<td>Gross</td>
<td>18.01.</td>
<td>Aberration correction, system layouts, optimization, realization aspects</td>
</tr>
<tr>
<td>12</td>
<td>Photometry</td>
<td>Gross</td>
<td>25.01.</td>
<td>Notations, fundamental laws, Lambert source, radiative transfer, photometry of optical systems, color theory</td>
</tr>
<tr>
<td>13</td>
<td>Illumination systems</td>
<td>Gross</td>
<td>01.02.</td>
<td>Light sources, basic systems, quality criteria, nonsequential raytrace</td>
</tr>
<tr>
<td>14</td>
<td>Metrology</td>
<td>Gross</td>
<td>08.02.</td>
<td>Measurement of basic parameters, quality measurements</td>
</tr>
</tbody>
</table>
Modelling of Optical Systems

- Principal purpose of calculations:

1. Solving the direct problem of understanding the properties: analysis

2. Solving the inverse problem: Finding the concrete system data for a required functionality: synthesis

Ref: W. Richter
- Classification of systems with field and aperture size

- Scheme is related to size, correction goals and etendue of the systems

- Aperture dominated: Disk lenses, microscopy, Collimator

- Field dominated: Projection lenses, camera lenses, Photographic lenses

- Spectral width as a correction requirement is missed in this chart
Optical System Examples

- Microscopic lens
- Camera lens
- Interferometer
- Telescope
- Endoscope
Optical System Examples

Lithographic lens

Fisheye lens

Eyepiece
Optical System Examples

Microscope

Spectrometer

Scan lens
Optical System Examples

Zoom system

Line generator

Auto focus sensor
Historical Instruments

- Fresnel lens lantern 1800
- Fresnel lens 1900
- Monocular telescope 1800
- Gregorian telescope 1770

Ref: University Arizona Museum
Historical Instruments

Zeiss Tessar

Zeiss Microscope 1900

Zeiss Microscope 1920

Ref: University Arizona Museum
Miniature Systems

- Fiber coupler
- Variable endoscope
- Endoscope with prism
- Mobile phone camera
- Microscopic lens
- Spectrometer

Ref: IOF, Jena
Ref: Leica
Ref: IMTEK
Complete Lithographic Maschine

Photomaske (Reticle)

Beleuchtungssystem

Excimer Laser

Strahlführung

Reticle Laderoboter

Projektionsobjektiv

Wafertisch

Wafer Laderoboter
Lithographic Optics

- EUV $\alpha$-Tool 2008
Early Data sheets and Calculation of Abbe

- First Apochromate of Abbe 1886
  Data sheet for prototyp production

- Diffraction theory and meaning of the numerical aperture

Ref: B. Dörband / H. Müller
Development of technological support for raytrace calculations

10 minutes per surface = 1/600 surface per second

Integrated Circuits
Transistors
Electron tubes
Integrated Circuits
parallel computing

100 million surfaces per second (12 CPUs)

"Moore’s Law"

Ref: V. Blahnik
Surface Contributions: Example

- Seidel aberrations: representation as sum of surface contributions possible
- Gives information on correction of a system
- Example: photographic lens
Basic Idea of Optimization

- Topology of the merit function in 2 dimensions
- Iterative down climbing in the topology
Mathematical description of the problem:

- **n** variable parameters
- **m** target values
- Jacobi system matrix of derivatives, influence of a parameter change on the various target values, sensitivity function
- Scalar merit function
- Gradient vector of topology
- Hesse matrix of 2nd derivatives

\[ \bar{x} \]
\[ \bar{f}(\bar{x}) \]
\[ J_{i,j} = \frac{\partial f_i}{\partial x_j} \]
\[ F(\bar{x}) = \sum_{i=1}^{m} w_i \cdot [y_i - f(\bar{x})]^2 \]
\[ g_j = \frac{\partial F}{\partial x_j} \]
\[ H_{jk} = \frac{\partial^2 F}{\partial x_j \partial x_k} \]
Goal of optimization:
Find the system layout which meets the required performance targets according of the specification

Formulation of performance criteria must be done for:
- Apertur rays
- Field points
- Wavelengths
- Optional several zoom or scan positions

Selection of performance criteria depends on the application:
- Ray aberrations
- Spot diameter
- Wavefornt description by Zernike coefficients, rms value
- Strehl ratio, Point spread function
- Contrast values for selected spatial frequencies
- Uniformity of illumination

Usual scenario:
Number of requirements and targets quite larger than degrees od freedom,
Therefore only solution with compromise possible
- **Merit function:**
  Weighted sum of deviations from target values

- **Formulation of target values:**
  1. fixed numbers
  2. one-sided interval (e.g. maximum value)
  3. interval

- **Problems:**
  1. linear dependence of variables
  2. internal contradiction of requirements
  3. initial value far off from final solution

- **Types of constraints:**
  1. exact condition (hard requirements)
  2. soft constraints: weighted target

- **Finding initial system setup:**
  1. modification of similar known solution
  2. Literature and patents
  3. Intuition and experience

\[
\Phi = \sum_{j=1,m} g_j \cdot \left( f_j^{ist} - f_j^{soll} \right)^2
\]
Characterization and description of the system delivers free variable parameters of the system:

- Radii
- Thickness of lenses, air distances
- Tilt and decenter
- Free diameter of components
- Material parameter, refractive indices and dispersion
- Aspherical coefficients
- Parameter of diffractive components
- Coefficients of gradient media

General experience:
- Radii as parameter very effective
- Benefit of thickness and distances only weak
- Material parameter can only be changes discrete
Constraints in the optimization of optical systems:

1. Discrete standardized radii (tools, metrology)
2. Total track
3. Discrete choice of glasses
4. Edge thickness of lenses (handling)
5. Center thickness of lenses (stability)
6. Coupling of distances (zoom systems, forced symmetry, ...)
7. Focal length, magnification, working distance
8. Image location, pupil location
9. Avoiding ghost images (no concentric surfaces)
10. Use of given components (vendor catalog, availability, costs)
Illustration of not useful results due to non-sufficient constraints
Boundary Conditions and Constraints

- Types of constraints
  1. Equation, rigid coupling, pick up
  2. One-sided limitation, inequality
  3. Double-sided limitation, interval

- Numerical realizations:
  1. Lagrange multiplier
  2. Penalty function
  3. Barrier function
  4. Regular variable, soft-constraint
- Typical merit function of an achromate
- Three solutions, only two are useful
System Design Phases

1. Paraxial layout:
   - specification data, magnification, aperture, pupil position, image location
   - distribution of refractive powers
   - locations of components
   - system size diameter / length
   - mechanical constraints
   - choice of materials for correcting color and field curvature

2. Correction/consideration of Seidel primary aberrations of 3rd order for ideal thin lenses, fixation of number of lenses

3. Insertion of finite thickness of components with remaining ray directions

4. Check of higher order aberrations

5. Final correction, fine tuning of compromise

6. Tolerancing, manufactability, cost, sensitivity, adjustment concepts
Number of Lenses

- Approximate number of spots over the field as a function of the number of lenses. Linear for small number of lenses. Depends on mono-/polychromatic design and aspherics.

- Diffraction limited systems with different field size and aperture.
- Existing solution modified
- Literature and patent collections
- Principal layout with ideal lenses
  successive insertion of thin lenses and equivalent thick lenses with correction control

- Approach of Shafer
  AC-surfaces, monochromatic, buried surfaces, aspherics
- Expert system
- Experience and genius
Optimization and Starting Point

- The initial starting point determines the final result.
- Only the next located solution without hill-climbing is found.
## Correction Effectiveness

- Effectiveness of correction features on aberration types

<table>
<thead>
<tr>
<th>Aberration</th>
<th>Primary Aberration</th>
<th>5th</th>
<th>Chromatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical Aberration</td>
<td>(a)</td>
<td>(c)</td>
<td>(e)</td>
</tr>
<tr>
<td>Coma</td>
<td>(f)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Astigmatism</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petzval Curvature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distortion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5th Order Spherical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial Color</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral Color</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary Spectrum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spherochromatism</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Action</th>
<th>Lens Parameters</th>
<th>Material</th>
<th>Special Surfaces</th>
<th>Struct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens Bending</td>
<td>(a)</td>
<td>(c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Splitting</td>
<td>(e)</td>
<td>(f)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Combination</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distances</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stop Position</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refractive Index</td>
<td>(b)</td>
<td>(d)</td>
<td>(g)</td>
<td>(h)</td>
</tr>
<tr>
<td>Dispersion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative Partial Disp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRIN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cemented Surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aplanatic Surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aspherical Surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mirror</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffractive Surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symmetry Principle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field Lens</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Makes a good impact.
- Makes a smaller impact.
- Makes a negligible impact.
- Zero influence.

Ref: H. Zügge
- Effect of bending a lens on spherical aberration
- Optimal bending:
  Minimize spherical aberration
- Dashed: thin lens theory
  Solid: think real lenses
- Vanishing SPH for $n=1.5$
  only for virtual imaging
- Correction of spherical aberration possible for:
  1. Larger values of the magnification parameter $|M|$
  2. Higher refractive indices

Ref: H. Zügge
- Correction of spherical aberration: Splitting of lenses
- Distribution of ray bending on several surfaces:
  - smaller incidence angles reduces the effect of nonlinearity
  - decreasing of contributions at every surface, but same sign
- Last example (e): one surface with compensating effect

Ref: H. Zügge
Sensitivity of a System

Representation of wave
Seidel coefficients [$\lambda$]

Double Gauss 1.4/50

Ref: H.Zügge
Structural Changes for Correction

- Lens bending
- Lens splitting
- Power combinations
- Distances

Ref: H. Zügge
- Removal of a lens by vanishing of the optical effect
- For single lens and cemented component
- Problem of vanishing index: Generation of higher orders of aberrations

a) Geometrical changes: radius and thickness
   1) adapt second radius of curvature
   2) shrink thickness to zero

b) Physical changes: index
Aplanatic Surfaces

- Aplanatic surfaces: zero spherical aberration:
  1. Ray through vertex \( s' = s = 0 \)
  2. concentric \( s' = s \) und \( u = u' \)
  3. Aplanatic \( ns = n's' \)

- Condition for aplanatic surface:
  \[
  r = \frac{ns}{n + n'} = \frac{n's'}{n + n'} = \frac{ss'}{s + s'}
  \]

- Virtual image location

- Applications:
  1. Microscopic objective lens
  2. Interferometer objective lens
Principles of Glass Selection in Optimization

- Design Rules for glass selection

- Different design goals:
  1. Color correction:
     - large dispersion difference desired
  2. Field flattening:
     - large index difference desired

Ref: H. Zügge
**Principle of Symmetry**

- Perfect symmetrical system: magnification $m = -1$
- Stop in centre of symmetry
- Symmetrical contributions of wave aberrations are doubled (spherical)
- Asymmetrical contributions of wave aberration vanishes $W(-x) = -W(x)$
- Easy correction of:
  - coma, distortion, chromatical change of magnification

![Diagram showing symmetrical system with front and rear parts and labeled rays $\lambda_1, \lambda_2, \lambda_3$]
Symmetry Principle

- Application of symmetry principle: photographic lenses
- Especially field dominant aberrations can be corrected
- Also approximate fulfillment of symmetry condition helps significantly: quasi symmetry
- Realization of quasi-symmetric setups in nearly all photographic systems

Ref: H. Zügge
Petzval Theorem for Field Curvature

- Petzval theorem for field curvature:
  1. formulation for surfaces
     \[
     \frac{1}{R_{ptz}} = -n_m' \sum_k \frac{n_k' - n_k}{n_k \cdot n_k' \cdot r_k}
     \]
  2. formulation for thin lenses (in air)
     \[
     \frac{1}{R_{ptz}} = -\sum_j \frac{1}{n_j \cdot f_j}
     \]
- Important: no dependence on bending
- Natural behavior: image curved towards system
- Problem: collecting systems with \( f > 0 \):
  If only positive lenses: \( R_{ptz} \) always negative
Flattening Meniscus Lenses

- Possible lenses / lens groups for correcting field curvature
- Interesting candidates: thick meniscus shaped lenses

\[
\frac{1}{R_{\text{ptz}}} = - \sum_k \frac{n_k' - n_k}{n_k \cdot n_k' \cdot r_k} = - \frac{1}{n \cdot f} + \left(\frac{n-1}{n}\right)^2 \cdot \frac{d}{r_1 r_2}
\]

1. Hoeghs mensicus: identical radii
   - Petzval sum zero
   - remaining positive refractive power

\[F' = \frac{(n-1)^2 d}{n \cdot r^2}\]

2. Concentric meniscus,
   - Petzval sum negative
   - weak negative focal length
   - refractive power for thickness d:

\[r_2 = r_1 - d\]

\[F' = -\frac{(n-1)d}{n r_1 (r_1 - d)}\]

3. Thick meniscus without refractive power
   Relation between radii

\[r_2 = r_1 - d \cdot \frac{n-1}{n}\]

\[\frac{1}{R_{\text{ptz}}} = \frac{(n-1)^2 \cdot d}{n r_1 [n r_1 - d \cdot (n-1)]} > 0\]
Field Curvature

- Correction of Petzval field curvature in lithographic lens for flat wafer

- Positive lenses: Green $h_j$ large
- Negative lenses: Blue $h_j$ small

- Correction principle: certain number of bulges

\[ \frac{1}{R} = -\sum_j \frac{F_j}{n_j} \]

\[ F = \sum_j \frac{h_j}{h_1} \cdot F_j \]
- Ray path of chief ray depends on stop position
Field Lenses

- Field lens: in or near image planes
- Influences only the chief ray: pupil shifted
- Critical: conjugation to image plane, surface errors sharply seen
Field Lens im Endoscope

without field lenses

with 1 field lens

with 2 field lenses

Ref: H. Zügge
Evolution of Eyepiece Designs

- **Loupe**
- **Monocentric**
- **Von-Hofe**
- **Plössl**
- **Erfle**
- **Erfle diffractive**
- **Wild**
- **Erfle type (Zeiss)**
- **Bertele**
- **Aspheric**
- **Kellner**
- **Kerber**
- **König**
- **Nagler 1**
- **Nagler 2**
- **Dilworth**
- **Scidmore**
- **Bertele**

Institute of Applied Physics
Friedrich-Schiller-Universität Jena
- Families of photographic lenses
- Long history
- Not unique
Medium Magnification Microscopic lenses
Development of Lithographic Lenses

- **a) Early systems**
- **b) Refractive spherical systems**
- **c) Refractive with aspheres and immersion**
- **d) Catadioptric cube systems**
- **e) Multi-axis catadioptric systems**
- **f) Uni-axis catadioptric systems**
- **g) EUV mirror systems**
Historical:
sequential workflow

Modern:
complex workflow with feedback and relationships

- Development
- Optical Design Tolerancing
- Mechanical Design
- Manufacturing
- Assembly Adjustment
- Performance Check

- Development
- Optical design Tolerancing
- phys-opt Simulation
- Mechanical Design
- Metrology
- Manufacturing components
- Control of buyed components
- Software Tests
- Integration Adjustment
- Researchlab
Introduction to Tolerancing

- Specifications are usually defined for the as-built system

- Optical designer has to develop an error budget that cover all influences on performance degradation as
  - design imperfections
  - manufacturing imperfections
  - integration and adjustment
  - environmental influences

- No optical system can be manufactured perfectly (as designed)
  - Surface quality, scratches, digs, micro roughness
  - Surface figure (radius, asphericity, slope error, astigmatic contributions, waviness)
  - Thickness (glass thickness and air distances)
  - Refractive index (n-value, n-homogeneity, birefringence)
  - Abbe number
  - Homogeneity of material (bubbles and inclusions)
  - Centering (orientation of components, wedge of lenses, angles of prisms, position of components)
  - Size of components (diameter of lenses, length of prism sides)
  - Special: gradient media deviations, diffractive elements, segmented surfaces,...

- Tolerancing and development of alignment concepts are essential parts of the optical design process

Ref: K. Uhlendorf
### Daten

<table>
<thead>
<tr>
<th>Beta</th>
<th>16 = 99,6</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>= 150,0</td>
</tr>
<tr>
<td>F1-10</td>
<td>= 120,0</td>
</tr>
<tr>
<td>F1-10</td>
<td>= 35,0</td>
</tr>
<tr>
<td>F8,9</td>
<td>= 35,0</td>
</tr>
</tbody>
</table>

### Abmessungen

<table>
<thead>
<tr>
<th>Radius</th>
<th>PLAN</th>
<th>PLAN</th>
<th>2,0700</th>
<th>2,5650</th>
<th>3,2210</th>
<th>13,428</th>
<th>6,3100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toleranzen</td>
<td>0,04</td>
<td>±0,03</td>
<td>±0,05</td>
<td>±0,02</td>
<td>±0,01</td>
<td>±0,02</td>
<td></td>
</tr>
<tr>
<td>K1</td>
<td>260</td>
<td>260</td>
<td>260</td>
<td>260</td>
<td>260</td>
<td>260</td>
<td>260</td>
</tr>
<tr>
<td>K2</td>
<td>1X0,1</td>
<td>1X0,1</td>
<td>1X0,1</td>
<td>1X0,1</td>
<td>1X0,1</td>
<td>1X0,1</td>
<td>1X0,1</td>
</tr>
</tbody>
</table>

### Freizeiten

| Freizeit | 1,5 | 1,5 | 3,9 | 4,5 | 6,2 | 8,7 | 9,4 |

<table>
<thead>
<tr>
<th>Ø</th>
<th>59,48</th>
<th>43,45</th>
<th>60,41</th>
<th>57,26</th>
<th>63,48</th>
</tr>
</thead>
</table>

### Toleranzen: Kombinationsfreie Fertigung

<table>
<thead>
<tr>
<th>Toleranz</th>
<th>±0,04</th>
<th>±0,03</th>
<th>±0,05</th>
<th>±0,02</th>
<th>±0,01</th>
<th>±0,02</th>
</tr>
</thead>
</table>

### Hinweise

- **Buchung:** 20
- **Radius:** 1X0,1
- **Schrauben:** -2
- **Prüfung:** 3,0 (1,0) 2,0 (0,4) 2,0 (0,4) 3,0 (0,6) 1,0 (0,2) 1,0 (0,2) |
- **Zentrier:** 9' 6' 8' 6' 2' 2'
- **Stundenzahl:** 34,15
## Tolerances: Typical Values

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Tolerance</th>
<th>Unit</th>
<th>&lt;10 mm</th>
<th>10...20 mm</th>
<th>20...30 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center thickness</td>
<td></td>
<td>mm</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Centering</td>
<td>Tilt angle</td>
<td>sek</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Decenter/offset</td>
<td>µm</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Roughness</td>
<td></td>
<td>nm</td>
<td>15</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Spherical/radius</td>
<td>spherical rings</td>
<td></td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>astigmatism rings</td>
<td></td>
<td>.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Asphericity</td>
<td>Global deviation</td>
<td>µm</td>
<td>1</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Global asphericity</td>
<td>µm</td>
<td>0.25</td>
<td>0.45</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Local deviation</td>
<td>µm</td>
<td>0.025</td>
<td>0.05</td>
<td>0.075</td>
</tr>
<tr>
<td></td>
<td>Slope error</td>
<td>rad</td>
<td>0.0005</td>
<td>0.0005</td>
<td>0.0005</td>
</tr>
</tbody>
</table>
Example Microscopic lens

Adjusting:
1. Axial shifting lens: focus
2. Clocking: astigmatism
3. Lateral shifting lens: coma

Ideal: Strehl $D_S = 99.62\%$
With tolerances: $D_S = 0.1\%$
After adjusting: $D_S = 99.3\%$

Ref.: M. Peschka
Adjustment and Compensation

- Successive steps of improvements

PSF (intensity normalized)

PSF (energy normalized)

With Tolerances

Step 1 (Z₄, Z₉)

Step 2 (Z₇, Z₈)

Step 3 (Z₅, Z₆)

Step 4 ~ Step 2 (Z₇, Z₈)

Ref.: M. Peschka
Drawing of Microscopic Lens with Housing