Design and Correction of Optical Systems

Lecture 12: Optical system classification

2014-06-25

Herbert Gross
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<tr>
<th>Week</th>
<th>Date</th>
<th>Topic</th>
<th>Notes</th>
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<tbody>
<tr>
<td>1</td>
<td>09.04.</td>
<td>Basics</td>
<td>Law of refraction, Fresnel formulas, optical system model, raytrace, calculation approaches</td>
</tr>
<tr>
<td>2</td>
<td>16.04.</td>
<td>Materials and Components</td>
<td>Dispersion, anormal dispersion, glass map, liquids and plastics, lenses, mirrors, aspheres, diffractive elements</td>
</tr>
<tr>
<td>3</td>
<td>23.04.</td>
<td>Paraxial Optics</td>
<td>Paraxial approximation, basic notations, imaging equation, multi-component systems, matrix calculation, Lagrange invariant, phase space visualization</td>
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<td>4</td>
<td>30.04.</td>
<td>Optical Systems</td>
<td>Pupil, ray sets and sampling, aperture and vignetting, telecentricity, symmetry, photometry</td>
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<td>5</td>
<td>07.05.</td>
<td>Geometrical Aberrations</td>
<td>Longitudinal and transverse aberrations, spot diagram, polynomial expansion, primary aberrations, chromatical aberrations, Seidels surface contributions</td>
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<td>6</td>
<td>14.05.</td>
<td>Wave Aberrations</td>
<td>Fermat principle and Eikonal, wave aberrations, expansion and higher orders, Zernike polynomials, measurement of system quality</td>
</tr>
<tr>
<td>7</td>
<td>21.05.</td>
<td>PSF and Transfer function</td>
<td>Diffraction, point spread function, PSF with aberrations, optical transfer function, Fourier imaging model</td>
</tr>
<tr>
<td>8</td>
<td>28.05.</td>
<td>Further Performance Criteria</td>
<td>Rayleigh and Marechal criteria, Strehl definition, 2-point resolution, MTF-based criteria, further options</td>
</tr>
<tr>
<td>9</td>
<td>04.06.</td>
<td>Optimization and Correction</td>
<td>Principles of optimization, initial setups, constraints, sensitivity, optimization of optical systems, global approaches</td>
</tr>
<tr>
<td>10</td>
<td>11.06.</td>
<td>Correction Principles I</td>
<td>Symmetry, lens bending, lens splitting, special options for spherical aberration, astigmatism, coma and distortion, aspheres</td>
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<tr>
<td>11</td>
<td>18.06.</td>
<td>Correction Principles II</td>
<td>Field flattening and Petzval theorem, chromatical correction, achromate, apochromate, sensitivity analysis, diffractive elements</td>
</tr>
<tr>
<td>12</td>
<td>25.06.</td>
<td>Optical System Classification</td>
<td>Overview, photographic lenses, microscopic objectives, lithographic systems, eyepieces, scan systems, telescopes, endoscopes</td>
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<tr>
<td>13</td>
<td>02.07.</td>
<td>Special System Examples</td>
<td>Zoom systems, confocal systems</td>
</tr>
<tr>
<td>14</td>
<td>09.07.</td>
<td>Further Topics</td>
<td>New system developments, modern aberration theory, ...</td>
</tr>
</tbody>
</table>
1. Overview
2. Achromates and apochromates
3. Collimators
4. Realy systems
5. Miscellaneous
6. Photographic lenses
7. Scan lenses
8. Lithographic lenses
9. Telescopes
10. Microscopic lenses
• 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
Classification: $\lambda$-L$_w$-Diagram

- Throughput as field-aperture product
- Additional dimension: spectral bandwidth
Achromate:
- Axial colour correction by cementing two different glasses
- Bending: correction of spherical aberration at the full aperture
- Aplanatic coma correction possible be clever choice of materials

Four possible solutions:
- Crown in front, two different bendings
- Flint in front, two different bendings

Typical:
- Correction for object in infinity
- Spherical correction at center wavelength with zone
- Diffraction limited for NA < 0.1
- Only very small field corrected
Achromate: Realization Versions

- **Advantage of cementing:**
  solid state setup is stable at sensitive middle surface with large curvature

- **Disadvantage:**
  loss of one degree of freedom

- **Different possible realization forms in practice**

  a) flint in front
  - edge contact
  - cemented

  b) crown in front
  - edge contact
  - cemented
  - contact on axis
  - broken, Gaussian setup
Achromate

- Longitudinal aberration
- Transverse aberration
- Spot diagram
Axial Color Correction

(a) Single element
BK7

(b) Achromat
BK7, F2

(c) Apochromat
FK51, KZFS11, SF6

Ref.: H. Zuegge
- Choice of at least one special glass
- Correction of secondary spectrum: anomalous partial dispersion
- At least one glass should deviate significantly from the normal glass line

Axial Colour: Apochromate

Graph showing the dispersion of light at different wavelengths (656 nm, 588 nm, 486 nm, 436 nm) with corresponding Δz values.
New Achromate

- Conventional achromate: strong bending of image shell, typical

\[ R_{ptz} = -1.3 \cdot f' \]

- Special selection of glasses:
  1. achromatization
     \[ \frac{F_1 + F_2}{v_1 + v_2} = 0 \]
  2. Petzval flattening
     \[ \frac{F_1}{n_1} + \frac{F_2}{n_2} = 0 \]

- Residual field curvature:

\[ \frac{1}{R_{ptz}} = -\frac{1}{v_2 - v_1} \cdot \left( \frac{v_1}{n_1} - \frac{v_2}{n_2} \right) \cdot \frac{1}{f'} \]

- Combined condition

\[ \frac{v_1}{v_2} = \frac{n_1}{n_2} \]

- But usually no spherical correction possible
Collimation

- Collimating source radiation:
  Finite divergence angle is reality
- Geometrical part due to finite size:
- Diffraction part:

\[
\theta_G = \frac{D}{f}
\]

\[
\theta_D = \frac{\lambda}{D}
\]

\[
\Delta \theta = -\frac{2\Delta z}{f} \cdot \sin u
\]
Monochromatic doublet

Correction only spherical and coma:
Seidel surface contributions
Limiting: astigmatism and curvature

Enlarged aperture: meniscus added
Large residual aberrations:
1. Astigmatism
2. Field curvature
- Correction comparable
- Better fit of pupil
Relay Systems: More Complicated Systems

- Improved performance with more lenses
- In particular better color correction

- Magnification $m = 0.2$
Relay Systems: 4f-Systems

- Basic system with achromates

- Split achromates
Relay Systems: 4f-Systems

- Double telecentric: magnification
- Wave transport: phase is invariant, use in phase imaging
- Use in Fourier-optical setups or pupil transfer systems

\[ \Gamma = -\frac{f_2}{f_1} \]

\[ E'(x, y) = \frac{1}{\Gamma} \cdot E\left(\frac{x}{\Gamma}, \frac{y}{\Gamma}\right) \]
Relay Systems: Periscope

- Major parts:
  1. Eyepiece
  2. Relay system, several stages
  3. Objective
  4. Turnable prism
Relay Systems: Endoscopes

- Different subsystems:
- Differences in performance, complexity, distance, weight
- Transport over large distances
- Combination of several relay subsystems
- Large field-angle objective lens
- Applications: Technical or medical

Different subsystems:

\[ W_{\text{rms}} [\lambda] \]

\[ y' \text{ [mm]} \]

486 nm 587 nm 656 nm

diffraction limit
- Example lens
- Aperture NA = 0.5
- Spherical correction with one surface
Beam Guiding Systems

- Transport of laser light over large distances
- Adaptation of beam diameter
- Solutions:
  Telescopes of Kepler or Galilei type
Families of photographic lenses
- Long history
- Not unique
Photographic Lenses

- Tessar
- Double Gauss
- Super Angulon
- Distagon
- Tele system
- Wide angle Fish-eye
Retrofocus Lenses

- Example lens 2
- Distagon
Fish-Eye-Lens

- Nikon 210°

- Pleon
  (air reconnaissance)
- Zoom lens
- Three moving groups
Handy Phone Objective lenses

- Examples

- US 7643225
  - L = 4.2 mm, F' = 2.8, f = 3.67 mm, 2w = 2x34°

- US 6844989
  - L = 6.0 mm, F' = 2.8, f = 4.0 mm, 2w = 2x31°

- EP 1357414
  - L = 5.37 mm, F' = 2.88, f = 3.32 mm, 2w = 2x33.9°

- Olympus 2
  - L = 7.5 mm, F' = 2.8, f = 4.57 mm, 2w = 2x33°

Ref: T. Steinich
Scan Systems: Introduction

- Basic setup

- Scan-magnification \( m = 1 \ldots 2 \) 

\[
m = \frac{d\varphi}{d\theta}
\]

- Virtual source point on curved line: special flattening formula

- Requirements:  
  - Duty cycle  
  - Speed  
  - Point resolution  
  - Accuracy  
  - Linearity  
  - Cost
Scan Systems: Introduction

- **Scan resolution:**
  Number of resolvable points in the field of view corresponds to angle resolution

- **Information capacity:**
  1. Resolvable points
  2. Speed of scanning

\[ N = \frac{L}{D_{\text{Airy}}} = \frac{2 \cdot D_{\text{Exp}} \cdot \theta_{\text{max}}}{\lambda} \]
Scan System

- Non-telecentric
- Scan angle 2x30°
- Monochromatic
- F-θ-corrected
Scan Systems: Introduction

- Deflecting components allows a field scan
- Mostly rotating mirrors
- Pre-objective scanning

- Post-objective scanning
Deflecting Components: Polygon Mirrors

- Rotating mirror with plane facets
- Pyramidal
- Prismatic
Evolution of Projection lenses

- Growing NA and field of view:
  - Increasing size of objective lenses
- Problems with correction, homogeneity, material cost, thermal effects
- Technological steps: aspherical surfaces, immersion, catadioptric designs

![Graph showing the evolution of NA and Volume in projection lenses with different categories like refractive, folded catadioptric, inline catadioptric, expectation hyper-NA, and design progress.](image-url)
Considerable reduction of length and diameter by aspherical surfaces
Fundamental System Groups

- Principal layout of a lithographic system
Milestones of Microlithography Optics

\[
\text{Res} = k_1 \cdot \frac{\lambda}{\text{NA}}
\]

<table>
<thead>
<tr>
<th>Stepper</th>
<th>David Mann (GCA) 4800</th>
<th>ASML/40</th>
<th>ASML/300</th>
<th>ASML/1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>0.28</td>
<td>0.40</td>
<td>0.57</td>
<td>0.85</td>
</tr>
<tr>
<td>Resolution (nm)</td>
<td>1400</td>
<td>700</td>
<td>250</td>
<td>80</td>
</tr>
<tr>
<td>No. of pixels x10^6</td>
<td>0.04</td>
<td>0.32</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Price (rel.)</td>
<td>1</td>
<td>10</td>
<td>80</td>
<td>450</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>2</td>
<td>20</td>
<td>250</td>
<td>750</td>
</tr>
</tbody>
</table>

Ref: W. Kaiser
Moores Law

- Historical development of shrinking feature size
- Moores law: factor 2 every two years
Lithographic Lens in Reality

Ref: Carl Zeiss AG
Lithographic Optics

- EUV $\alpha$-Tool 2008
Lithographic Optics

- H-Design
Lithographic Optics

- I-Design
Lithographic Optics

- X-Design
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
Field Flatness

- Principle of multi-bulges to reduce Petzval sum

\[
\frac{1}{r_p} = -n' \cdot \sum_k \frac{1}{n_k \cdot f_k}
\]

- Seidel contributions show principle
Projection Processing Modes

- Different process modes:
  1. Full field
  2. Scanning
  3. Step and repeat
Resolution

- Lateral resolution (CD)
  \[ k_1 = 0.25 \ldots 0.5 \]
- Axial resolution

- High NA:
  \[ \Delta z = k_2 \cdot \frac{n \cdot \lambda_0}{NA^2} \cdot \frac{1 + \sqrt{1 - (NA/n)^2}}{2} \]
- Influence:
  Wavelength and NA
- Diagram: \( k_1 = 0.36, k_2 = 0.28 \)

\[ \Delta x = k_1 \cdot \frac{\lambda_0}{NA} \]
\[ \Delta z = k_2 \cdot \frac{n \cdot \lambda_0}{NA^2} \]
Basic Refractive Telescopes

- Kepler typ:
  - internal focus
  - longer total track
  - $\Gamma > 0$

- Galilei typ:
  - no internal focus
  - shorter total track
  - $\Gamma < 0$
Catadioptric Telescopes

- Maksutov compact

- Klevtsov
Astronomical Telescope

Primary and secondary mirror
Four-Mirror Schiefspiegler Telescopes

- Solution Variants
Catadioptric Telescopes

- Schmidt Telescope
  - Aspherical corrector plate
  - Residual chromatical aberrations
  - Achromatic corrector plate possible
Evolution of Eyepiece Designs

- Loupe
- Monocentric
- Von-Hofe
- Plössl
- Erfle
- Erfle type (Zeiss)
- Erfle diffractive
- Scidmore
- Bertele
- Wild
- Huygens
- Ramsden
- Kellner
- Kerber
- König
- Nagler 1
- Nagler 2
- Bertele Aspheric
- Dilworth
Eyepiece: Notations

- Field lens reduces chief ray height
- Eye lens adapts pupil diameter
- Matching of:
  1. Field of view
  2. Pupil diameter
  3. Pupil location
- Eye relief:
  - distance between last lens surface and eye cornea
  - required: 15 mm
  - with eyeglasses: 20 mm
- Pupil size: 2-8 mm
Kellner Eyepiece

- Corresponds to Ramsden type
- Field lens moved
- Eye lens achromatized
Abbe Orthoscopic Eyepiece

- Distortion corrected
- General problems with eyepieces:
  - remote eye pupil
  - typical eye relief 22 mm
Application Fields of Microscopy

Ref: M. Kempe
Image Planes and Pupils

- Principal setup of a classical optical microscope
- Upper row: image planes
- Lower row: pupil planes
- Köhler setup
Microscope with Infinite Image Setup

- Basic microscopic system with infinite image location and tube lens
- Magnification of the first stage:

\[ m_{\text{obj}} = \frac{f_{\text{tube}}}{f_{\text{obj}}} \]

- Magnification of the complete setup

\[ m_{\text{micro}} = \frac{f_{\text{tube}}}{f_{\text{obj}}} \cdot \frac{250 \text{ mm}}{f_{\text{eye}}} \]

- Exit pupil size

\[ D_{\text{Exp}} = \frac{2 \cdot f_{\text{obj}} \cdot NA'}{m_{\text{obj}}} \]

![Microscope Diagram](attachment:image.png)
Upright-Microscope

- Sub-systems:
  1. Detection / Imaging path
     1.1 objective lens
     1.2 tube with tube lens and binocular beam splitter
     1.3 eyepieces
     1.4 optional equipment for photo-detection
  2. Illumination
     2.1 lamps with collector and filters
     2.2 field aperture
     2.3 condenser with aperture stop
Stereo microscopes  | Upright microscopes  | Inverse microscopes

Routine microscopes

From M. Kempe
Microscope Objective Lens: Performance Classes

- Classification:
  1. performance in colour correction
  2. correction in field flattening
- Division is rough
- Notation of quality classes depends on vendors
  (Neofluar, achro-plane, semi-apochromate,...)

<table>
<thead>
<tr>
<th>Improved field flatness</th>
<th>no</th>
<th>Achromate</th>
<th>Fluorite</th>
<th>Apochromat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plan</td>
<td>Plan-achromat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>improved colour correction</td>
<td></td>
<td></td>
<td></td>
<td>Plan-Fluorite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Plan-Apochromat</td>
</tr>
</tbody>
</table>
Microscope Objective Lens: Structure

- Typical parts of lens structure for high NA-objective lenses
- Separation of the lens setup in 3 major sections

**a**
- front part:
  1. spherical aberration: only small
  2. coma: only small
  3. astigmatism: only small
  4. curvature: only small

**b**
- middle part:
  1. spherical aberration: correction
  2. color: correction
  3. coma: correction

**c**
- rear part:
  1. curvature: correction
  2. astigmatism: correction
  3. color: correction
Microscope Objective Lens Types

- Medium magnification system 40x0.65
- High NA system 100x0.9 without field flattening
- High NA system 100x0.9 with flat field
- Large-working distance objective lens 40x0.65
Microscope Objective Lens: Correcting lens

- Floating element to adjust and correct spherical aberration

- Applications:
  1. different thickness values of cover glass
  2. index mismatch at the sample
- Object space telecentric
- Real rear stop is not defining the pupil
- Collimated outgoing beam
- Exit pupil usually not accessible
Illumination Optics: Overview

- Instrumental realizations

a) incident illumination
   bright field

b) incident illumination
   dark field

c) transmitted illumination
   bright field

d) transmitted illumination
   dark field
- Telescopic setup: common main objective lens
- View along the axis