Design and Correction of Optical Systems

Lecture 12: Optical system classification
2016-06-22
Herbert Gross
### Preliminary Schedule

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<thead>
<tr>
<th>Date</th>
<th>Topic</th>
<th>Details</th>
</tr>
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<tbody>
<tr>
<td>06.04.</td>
<td>Basics</td>
<td>Law of refraction, Fresnel formulas, optical system model, raytrace, calculation approaches</td>
</tr>
<tr>
<td>13.04.</td>
<td>Materials and Components</td>
<td>Dispersion, anormal dispersion, glass map, liquids and plastics, lenses, mirrors, aspheres, diffractive elements</td>
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<tr>
<td>20.04.</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>27.04.</td>
<td>Optical Systems</td>
<td>Pupil, ray sets and sampling, aperture and vignetting, telecentricity, symmetry, photometry</td>
</tr>
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<td>04.05.</td>
<td>Geometrical Aberrations</td>
<td>Longitudinal and transverse aberrations, spot diagram, polynomial expansion, primary aberrations, chromatical aberrations, Seidels surface contributions</td>
</tr>
<tr>
<td>11.05.</td>
<td>Wave Aberrations</td>
<td>Fermat principle and Eikonal, wave aberrations, expansion and higher orders, Zernike polynomials, measurement of system quality</td>
</tr>
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<td>18.05.</td>
<td>PSF and Transfer function</td>
<td>Diffraction, point spread function, PSF with aberrations, optical transfer function, Fourier imaging model</td>
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<tr>
<td>25.05.</td>
<td>Further Performance Criteria</td>
<td>Line of sight, apodization, edges and lines, pupil aberrations, sine condition, induced aberrations, vectorial aberrations Fourier imaging, caustics</td>
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<tr>
<td>01.06.</td>
<td>Optimization and Correction</td>
<td>Principles of optimization, initial setups, constraints, sensitivity, optimization of optical systems, global approaches</td>
</tr>
<tr>
<td>08.06.</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>15.06.</td>
<td>Correction Principles II</td>
<td>Field flattening and Petzval theorem, chromatical correction, achromate, apochromate, sensitivity analysis, diffractive elements</td>
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<tr>
<td>22.06.</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>29.06.</td>
<td>Special System Examples</td>
<td>Zoom systems, confocal systems</td>
</tr>
<tr>
<td>06.07.</td>
<td>Further Topics</td>
<td>New system developments, modern aberration theory,...</td>
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</table>
1. Overview
2. Achromates and apochromates
3. Collimators
4. Relay 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

- Achromate
- Longitudinal aberration
- Transverse aberration
- Spot diagram
- 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

- 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
New Achromate

- Conventional achromate: strong bending of image shell, typical
  \[ R_{ptz} = -1.3 \cdot f' \]

- Special selection of glasses:
  1. achromatization
     \[ \frac{F_1}{v_1} + \frac{F_2}{v_2} = 0 \]
  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:
- Defocussing contribution to divergence

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

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

\[ \Delta\theta = -\frac{2\Delta z}{f} \cdot \sin u \]
- Monochromatic doublet
- Correction only spherical and coma:
  Seidel surface contributions
  Limiting : astigmatism and curvature

- Enlarged aperture : meniscus added
Relay Systems: Achromate

- Large residual aberrations:
  1. Astigmatism
  2. Field curvature

![Diagram](image)

**a) spherical aberration**

\[
\frac{y_p}{y_{p,\text{max}}} = 1.0
\]

**b) astigmatic field curves**

\[
\frac{y'}{y'_{\text{max}}} \text{ and } \tan, \text{ sag}
\]

**c) distortion**

\[
\frac{y'}{y'_{\text{max}}} = 1.0
\]
Relay Systems: Achromate with Field Lens

- Correction comparable
- Better fit of pupil
Relay Systems: More Complicated Systems

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

- Magnification $m = 0.2$

![Diagram of relay systems with improved performance and better color correction](attachment:relay_systems_diagram.png)
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: 4f-Systems

- Basic system with achromates

- Split achromates
Relay Systems: Endoscopes

- Different subsystems:
- Differences in performance, complexity, distance, weight
Relay Systems: Endoscopes

- Transport over large distances
- Combination of several relay subsystems
- Large field-angle objective lens
- Applications: Technical or medical

Different subsystems:

![Diagram of relay systems with objective, 1st relay, 2nd relay, and 3rd relay]
Relay Systems: Periscope

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

- Transport of laser light over large distances
- Adaptation of beam diameter
- Solutions:
  Telescopes of Kepler or Galilei type
Interferometer Collimator Lens

- Example lens
- Aperture NA = 0.5
- Spherical correction with one surface
- 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**

<table>
<thead>
<tr>
<th>Lens Description</th>
<th>Optical Parameters</th>
</tr>
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<tbody>
<tr>
<td>US 7643225</td>
<td>L = 4.2 mm, F' = 2.8, f = 3.67 mm, 2w = 2x34°</td>
</tr>
<tr>
<td>US 6844989</td>
<td>L = 6.0 mm, F' = 2.8, f = 4.0 mm, 2w = 2x31°</td>
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<tr>
<td>EP 1357414</td>
<td>L = 5.37 mm, F' = 2.88, f = 3.32 mm, 2w = 2x33.9°</td>
</tr>
<tr>
<td>Olympus 2</td>
<td>L = 7.5 mm, F' = 2.8, f = 4.57 mm, 2w = 2x33°</td>
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</tbody>
</table>

Ref: T. Steinich
Scan Systems: Introduction

- Basic setup

- Scan-magnification \( m = 1 \ldots 2 \) \( \quad m = \frac{d\varphi}{d\theta} \)

- Virtual source point on curved line: special flattening formula

- Requirements: - Duty cycle - Point resolution
  - Speed - 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

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

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

![Graphs showing standard distortion, f-θ-distortion, and wave aberration.](image)
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
Fundamental System Groups

- Principal layout of a lithographic system
Moores Law

- Historical development of shrinking feature size
- Moores law: factor 2 every two years
Development of Stepper Lenses

Milestones of Microlithography Optics

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

First stepper lens

First lens for volume production @ 

<table>
<thead>
<tr>
<th>Stepper</th>
<th>David Mann (GCA) 4800</th>
<th>ASML/40</th>
<th>ASML/300</th>
<th>ASML/1200</th>
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<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 x10^9</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>
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</tbody>
</table>

Ref: W. Kaiser
Lithographic Lens in Reality

Ref: Carl Zeiss AG
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**
Lithographic Optics

- H-Design
Lithographic Optics

- I-Design
Lithographic Optics

- X-Design
Field Flatness

- Principle of multi-bulges to reduce Petzval sum

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

- Seidel contributions show principle
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: \( k_1 = 0.36 \), \( k_2 = 0.28 \)

\[ \Delta x = k_1 \cdot \frac{\lambda_0}{NA} \]

\[ \Delta z = k_2 \cdot \frac{n \cdot \lambda_0}{NA^2} \]
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
Size Reduction by Aspheres

- Considerable reduction of length and diameter by aspherical surfaces

- a) NA = 0.7 spherical
- b) NA = 0.8 spherical
- c) NA = 0.8 aspherical
- d) NA = 0.9 aspherical

-9%  
-13%
- Different process modes:
  1. Full field
  2. Scanning
  3. Step and repeat
Lithographic Optics

- EUV $\alpha$-Tool 2008
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 diffractive
- Wild
- Kellner
- Ramsden
- Huygens
- Kerber
- König
- Nagler 1
- Nagler 2
- Bertele
- Aspheric
- Dilworth
- Scidmore
- Bertele
- Erfle type
- Erfle type (Zeiss)
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

<table>
<thead>
<tr>
<th>DIOPTER</th>
<th>DIOPTER</th>
<th>DIOPTER</th>
</tr>
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<tbody>
<tr>
<td>-1.000</td>
<td>-3.000</td>
<td>-20.00</td>
</tr>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
</tr>
<tr>
<td>1.000</td>
<td>3.000</td>
<td>20.00</td>
</tr>
</tbody>
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Longitudinal Spherical Aberration

Astigmatic Field Curves

Distortion (%)

0° 10° 18° 20 arcmin
Application Fields of Microscopy

Microscopy

Research

Biomedical basic research
- Cell biology
- Biological development
- Toxicology, ...

Material research
- Micro system technology
- Geology
- Polymer chemistry

Routine applications

Medical routine
- Pathology
- Clinical routine
- Forensic, ...

Microscopic surgery
- Ophthalmology

Industrial routine
- Pharmacy
- Semiconductor inspection
- Semiconductor manufacturing

Ref: M. Kempe
Image Planes and Pupils

- Principal setup of a classical optical microscope
- Upper row: image planes
- Lower row: pupil planes
- Köhler setup

Diagram showing the principal setup of a classical optical microscope with labeled components such as source, collector, condenser, objective, tube lens, eyepiece, eye, field stop, aperture stop, exit pupil, objective, intermediate image, and image.
Microscope with Infinite Image Setup

- Basic microscopic system with infinite image location and tube lens
- Magnification of the first stage:
  \[ m_{obj} = \frac{f_{tube}}{f_{obj}} \]
- Magnification of the complete setup
  \[ m_{micro} = \frac{f_{tube}}{f_{obj}} \cdot \frac{250 \text{ mm}}{f_{eye}} \]
- Exit pupil size
  \[ D_{Exp} = 2 \cdot f_{obj} \cdot NA' = \frac{2 \cdot f_{obj} \cdot NA}{m_{obj}} \]
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
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>improved colour correction</td>
<td>Plan</td>
<td>Plan-achromat</td>
<td>Plan-Fluorite</td>
<td>Plan-Apochromat</td>
</tr>
</tbody>
</table>
- 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
Floating element to adjust and correct spherical aberration

Applications:
1. different thickness values of cover glass
2. index mismatch at the sample
Microscope Objective Lens: Pupil

- 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
Stereo Microscope

- Telescopic setup: common main objective lens
- View along the axis