Design and Correction of Optical Systems

Lecture 12: Optical system classification
2013-07-03
Herbert Gross
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<th>Date</th>
<th>Topic</th>
<th>Details</th>
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<td>10.04.</td>
<td>Basics</td>
<td>Law of refraction, Fresnel formulas, optical system model, raytrace, calculation approaches</td>
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<td>2</td>
<td>17.04.</td>
<td>Materials and Components</td>
<td>Dispersion, anomalous dispersion, glass map, liquids and plastics, lenses, mirrors, aspheres, diffractive elements</td>
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<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>Pupil, ray sets and sampling, aperture and vignetting, telecentricity, symmetry, photometry</td>
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<td>Longitudinal and transverse aberrations, spot diagram, polynomial expansion, primary aberrations, chromatic aberrations, Seidel's surface contributions</td>
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<td>Wave Aberrations</td>
<td>Fermat principle and Eikonal, wave aberrations, expansion and higher orders, Zernike polynomials, measurement of system quality</td>
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<td>7</td>
<td>29.05.</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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<td>8</td>
<td>05.06.</td>
<td>Further Performance Criteria</td>
<td>Rayleigh and Marechal criteria, Strehl definition, 2-point resolution, MTF-based criteria, further options</td>
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<td>9</td>
<td>12.06.</td>
<td>Optimization and Correction</td>
<td>Principles of optimization, initial setups, constraints, sensitivity, optimization of optical systems, global approaches</td>
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<tr>
<td>10</td>
<td>19.06.</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>26.06.</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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<td>12</td>
<td>03.07.</td>
<td>Optical System Classification</td>
<td>Overview, photographic lenses, microscopic objectives, lithographic systems, eyepieces, scan systems, telescopes, endoscopes</td>
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<td>13</td>
<td>10.07.</td>
<td>Special System Examples</td>
<td>Zoom systems, confocal systems</td>
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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
- 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 by 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
  b) crown in front
Achromate: Basic Formulas

- **Idea:**
  1. Two thin lenses close together with different materials
  2. Total power

\[ F = F_1 + F_2 \]

- **Achromatic correction condition**

\[ \frac{F_1}{v_1} + \frac{F_2}{v_2} = 0 \]

- **Individual power values**

\[ F_1 = \frac{1}{1 - \frac{v_2}{v_1}} \cdot F \]
\[ F_2 = \frac{1}{1 - \frac{v_1}{v_2}} \cdot F \]

- **Properties:**
  1. One positive and one negative lens necessary
  2. Two different sequences of plus (crown) / minus (flint)
  3. Large \( v \)-difference relaxes the bendings
  4. Achromatic correction independent from bending
  5. Bending corrects spherical aberration at the margin
  6. Aplanatic coma correction for special glass choices
  7. Further optimization of materials reduces the spherical zonal aberration
Achromate: Correction

- Cemented achromate:
  6 degrees of freedom:
  3 radii, 2 indices, ratio \( n_1/n_2 \)

- Correction of spherical aberration:
  diverging cemented surface with positive spherical contribution for \( n_{\text{neg}} > n_{\text{pos}} \)

- Choice of glass: possible goals
  1. aplanatic coma correction
  2. minimization of spherochromatism
  3. minimization of secondary spectrum

- Bending has no impact on chromatical correction:
  is used to correct spherical aberration at the edge

- Three solution regions for bending
  1. no spherical correction
  2. two equivalent solutions
  3. one aplanatic solution, very stable

\[ \Delta s'_{\text{rim}} \]
Achromatic solutions in the Glass Diagram

- Flint negative lens
- Crown positive lens
- Achromat
Achromate

- 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
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:

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

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

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

- 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
Relay Systems: Achromate with Field Lens

- Correction comparable
- Better fit of pupil

![Graphs showing spherical aberration, astigmatic field curves, and distortion](image)
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
- 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
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: Endoscopes](image)
Interferometer Collimator Lens

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

![Diagram of interferometer collimator lens with possible surfaces under test and graph showing W_{rms}[\lambda] vs. w[^\circ]]
Beam Guiding Systems

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

![Diagram showing different beam guiding systems](image)
- 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**
    - \( L = 4.2 \text{ mm}, F' = 2.8, f = 3.67 \text{ mm}, 2w = 2 \times 34^\circ \)

  - **US 6844989**
    - \( L = 6.0 \text{ mm}, F' = 2.8, f = 4.0 \text{ mm}, 2w = 2 \times 31^\circ \)

  - **EP 1357414**
    - \( L = 5.37 \text{ mm}, F' = 2.88, f = 3.32 \text{ mm}, 2w = 2 \times 33.9^\circ \)

  - **Olympus 2**
    - \( L = 7.5 \text{ mm}, F' = 2.8, f = 4.57 \text{ mm}, 2w = 2 \times 33^\circ \)

Ref: T. Steinich
Basic setup

- Scan-magnification $m = 1\ldots2$
  \[ m = \frac{d\varphi}{d\theta} \]

- 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

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

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

![Graphs and diagrams showing the effects of 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
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
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

-13%  
-9%
Fundamental System Groups

- Principal layout of a lithographic system
### Milestones of Microlithography Optics

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

<table>
<thead>
<tr>
<th>Stepper</th>
<th>436nm</th>
<th>365nm</th>
<th>248nm</th>
<th>193nm</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
Moores Law

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

![Graph showing historical development of shrinking feature size and Moores Law](image)
Lithographic Lens in Reality

Ref: Carl Zeiss AG
Lithographic Lens Example Layouts

1. relay group

reticle
stop
mask

wafer
mirror

intermediate image

2. relay group

reticle
stop

mirror with relay group
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

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

- Seidel contributions show principle
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

\[ r = 2f \]

\[ \text{focal plane (curved)} \]

\[ \text{primary mirror} \]

\[ \text{stop} \]

\[ \text{corrector plate} \]

\[ \text{marginal rays} \]

\[ \text{field} \]

\[ \text{focus} \]

\[ \text{N-BK7, N-F2} \]
Evolution of Eyepiece Designs

Loupe

Monocentric

Von-Hofe

Plössl

Erfle

Erfle diffractive

Erfle type

Erfle type (Zeiss)

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
- 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

![Diagram of eyepiece and distortion curves](image-url)
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, ...
- Industrial routine
  - Pharmacy
  - semiconductor inspection
  - semiconductor manufacturing
- Routine applications
  - Microscopic surgery
  - ophthalmology
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
  \[ D_{\text{Exp}} = 2 \cdot f_{\text{obj}} \cdot NA' = \frac{2 \cdot f_{\text{obj}} \cdot NA}{m_{\text{obj}}} \]
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
Microscope Stands

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>Improved colour correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
<td>Achromate</td>
</tr>
<tr>
<td>Plan</td>
<td>Plan-achromat</td>
</tr>
<tr>
<td></td>
<td>Fluorite</td>
</tr>
<tr>
<td></td>
<td>Apochromat</td>
</tr>
<tr>
<td></td>
<td>Plan-Fluorite</td>
</tr>
<tr>
<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
Stereo Microscope

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