Medical Photonics Lecture
Optical Engineering

Lecture 12: Illumination Systems
2019-07-03
Herbert Gross

Summer term 2019
<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>Zhong</td>
<td>10.04.</td>
<td>Materials, dispersion, ray picture, geometrical approach, paraxial approximation</td>
</tr>
<tr>
<td>2</td>
<td>Geometrical optics</td>
<td>Zhong</td>
<td>17.04.</td>
<td>Ray tracing, matrix approach, aberrations, imaging, Lagrange invariant</td>
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<tr>
<td>3</td>
<td>Diffraction</td>
<td>Zhong</td>
<td>24.04.</td>
<td>Basic phenomena, wave optics, interference, diffraction calculation, point spread function, transfer function</td>
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<tr>
<td>4</td>
<td>Components</td>
<td>Kempe</td>
<td>08.05.</td>
<td>Lenses, micro-optics, mirrors, prisms, gratings</td>
</tr>
<tr>
<td>5</td>
<td>Optical systems</td>
<td>Zhong</td>
<td>15.05.</td>
<td>Field, aperture, pupil, magnification, infinity cases, lens makers formula, etendue, vignetting</td>
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<tr>
<td>6</td>
<td>Aberrations</td>
<td>Zhong</td>
<td>22.05.</td>
<td>Introduction, primary aberrations, miscellaneous</td>
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<tr>
<td>7</td>
<td>Image quality</td>
<td>Zhong</td>
<td>29.05.</td>
<td>Spot, ray aberration curves, PSF and MTF, criteria</td>
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<tr>
<td>8</td>
<td>Instruments I</td>
<td>Kempe</td>
<td>05.06.</td>
<td>Human eye, loupe, eyepieces, photographic lenses, zoom lenses, telescopes</td>
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<tr>
<td>9</td>
<td>Instruments II</td>
<td>Kempe</td>
<td>12.06.</td>
<td>Microscopic systems, micro objectives, illumination, scanning microscopes, contrasts</td>
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<tr>
<td>10</td>
<td>Instruments III</td>
<td>Kempe</td>
<td>19.06.</td>
<td>Medical optical systems, endoscopes, ophthalmic devices, surgical microscopes</td>
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<tr>
<td>11</td>
<td>Photometry</td>
<td>Zhong</td>
<td>26.06.</td>
<td>Notations, fundamental laws, Lambert source, radiative transfer, photometry of optical systems, color theory</td>
</tr>
<tr>
<td>12</td>
<td>Illumination systems</td>
<td>Gross</td>
<td>03.07.</td>
<td>Light sources, basic systems, quality criteria, nonsequential raytrace</td>
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<tr>
<td>13</td>
<td>Metrology</td>
<td>Gross</td>
<td>10.07.</td>
<td>Measurement of basic parameters, quality measurements</td>
</tr>
</tbody>
</table>
Content

- Types of light sources
- LEDs
- Laser sources
- Components
- Illumination systems
- Calculation of illumination setups
- Beam profiling
Photometric Properties

- Relations of the 4 main definitions
- Cassarly's diamond

Ref.: J. Muschaweck
## Types of Light Sources

<table>
<thead>
<tr>
<th>Source type</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal radiator</td>
<td>Black body</td>
</tr>
<tr>
<td></td>
<td>Globar sources</td>
</tr>
<tr>
<td></td>
<td>Incandescent bulbs</td>
</tr>
<tr>
<td></td>
<td>Electrical arc lamps</td>
</tr>
<tr>
<td>Luminescent radiator</td>
<td>Discharge lamps</td>
</tr>
<tr>
<td></td>
<td>Fluorescent tube</td>
</tr>
<tr>
<td></td>
<td>Semiconductor diodes, LED</td>
</tr>
<tr>
<td></td>
<td>Laser</td>
</tr>
</tbody>
</table>
## Types of Light Sources

<table>
<thead>
<tr>
<th>source type</th>
<th>coherence</th>
<th>spectrum</th>
<th>directionality</th>
<th>brightness</th>
</tr>
</thead>
<tbody>
<tr>
<td>lamp</td>
<td>incoherent</td>
<td>broad band white</td>
<td>all</td>
<td>low</td>
</tr>
<tr>
<td>laser</td>
<td>coherent</td>
<td>single wavelength monochromatic</td>
<td>directed beam</td>
<td>very high</td>
</tr>
<tr>
<td>super continuum source</td>
<td>coherent</td>
<td>broad band white</td>
<td>directed beam</td>
<td>high</td>
</tr>
</tbody>
</table>

Ref: I. Babushkin
Lamps

- Different types of lamps
Arrays - Illumination Systems

Illumination LED lighting
Realistic Light Source Models

CAD model of light sources:
1. Real geometry and materials
2. Real radiance distributions

Bulb lamp

XBO-lamp
Incandescent Bulbs

- Gray / black radiator
- Finite lifetime by evaporation and contamination on inner glass bulb
- Efficiency decreases with time
Incandescent Bulbs

- Efficiency
  \[ \eta = \frac{\Phi}{P} = 16...34 \frac{lm}{W} \approx 2...4\% \]

- \( \eta \) depends on temperature \( T \)
  - \( T \) in K
  - Angle distribution:
    - non-uniform, inner surfaces have higher \( T \)
XBO - Xenon Source

- Geometry
- Luminance distribution
Angle Indicatrix Hg-Lamp high Pressure

- Polar diagram of angle-dependent intensity
- Vertical line: Axis Anode - Cathode
Spectral Distributions

- Xenon lamp
  Line spectrum

- HG-Xe-lamp
Spectral Distributions of Lamps
Spectrum of HBO Mercury Lamp

- Typical line spectrum
- Several lines in UV

Ref.: M. Kempe / www.zeiss-campus.magnet.fsu.edu
## Comparison of Light Source Properties

<table>
<thead>
<tr>
<th>Lamp type</th>
<th>Lamp type</th>
<th>Efficiency in lm/W</th>
<th>Lifetime in h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent lamp</td>
<td>16 – 34</td>
<td>&lt; 1500</td>
<td></td>
</tr>
<tr>
<td>Fluorescent lamp</td>
<td>80</td>
<td>7000 – 18000</td>
<td></td>
</tr>
<tr>
<td>Halogen bulb</td>
<td>25</td>
<td>2000 – 4000</td>
<td></td>
</tr>
<tr>
<td>Fluorescent tube Na /Hg low pressure</td>
<td>100 – 200</td>
<td>14000 – 18000</td>
<td></td>
</tr>
<tr>
<td>Hg high pressure</td>
<td>50 – 120</td>
<td>24000</td>
<td></td>
</tr>
<tr>
<td>Hg very high pressure</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xenon</td>
<td>15 – 50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hg and Xenon</td>
<td>22 – 53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semiconductor diode, LED LED, red (615 nm)</td>
<td>50 – 100</td>
<td>20000 – 50000</td>
<td></td>
</tr>
<tr>
<td>LED, blue (460 nm)</td>
<td>10</td>
<td>20000 – 50000</td>
<td></td>
</tr>
<tr>
<td>LED, green (525 nm)</td>
<td>20 – 30</td>
<td>20000 – 50000</td>
<td></td>
</tr>
<tr>
<td>LED, white</td>
<td>20 – 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic light emitting diode, OLED yellow</td>
<td>35</td>
<td>30000 at 100 Cd/m²</td>
<td></td>
</tr>
<tr>
<td>blue</td>
<td>10</td>
<td>3000 – 10000 at 150 Cd/m²</td>
<td></td>
</tr>
<tr>
<td>white</td>
<td>20</td>
<td>5000 – 20000 at 150 Cd/m²</td>
<td></td>
</tr>
<tr>
<td>Laser</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semiconductor laser</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YAG solid state laser</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argon gas gas laser</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Efficiency

- Ratio of light power to electrical/excitation power

\[ \eta = \frac{P_{\text{light}}}{P_{\text{in}}} \]

- Black body radiation as reference

\[ \eta_{\text{Planck}}^{\text{max}} = 94 \frac{\text{lm}}{W} \approx 14\% \]
LED

- View of a light emitting diode
- View along axis in distance 5 mm: circular symmetry is a nightmare
- View from the side
  - raytrace model
  - measured component

Ref.: J. Muschaweck
LEDs

- Family of commercial visible LEDs
- Different sizes, brightness,...

Ref.: J. Muschaweck
<table>
<thead>
<tr>
<th>Material</th>
<th>Color</th>
<th>Wavelength in nm</th>
<th>FWHM in nm</th>
<th>Luminance in cd/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAsP</td>
<td>NIR</td>
<td>1300</td>
<td>50 – 150</td>
<td></td>
</tr>
<tr>
<td>GaAs:Si</td>
<td>NIR</td>
<td>940</td>
<td>50 – 150</td>
<td></td>
</tr>
<tr>
<td>GaAs:Zn</td>
<td>NIR</td>
<td>900</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>GaAlAs</td>
<td>NIR</td>
<td>880</td>
<td>30 – 60</td>
<td></td>
</tr>
<tr>
<td>GaP:Zn,N</td>
<td>dark red</td>
<td>700</td>
<td></td>
<td></td>
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<tr>
<td>GaP</td>
<td>red</td>
<td>690</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>GaAlAs</td>
<td>red</td>
<td>660</td>
<td>40</td>
<td>2570</td>
</tr>
<tr>
<td>GaAs₆P₄</td>
<td>red</td>
<td>660</td>
<td>40</td>
<td>2570</td>
</tr>
<tr>
<td>GaAs₀.₃₅P₀.₆₅:N</td>
<td>orange</td>
<td>630</td>
<td></td>
<td></td>
</tr>
<tr>
<td>InGaAlP</td>
<td>red</td>
<td>618</td>
<td>20</td>
<td>2 × 10⁷</td>
</tr>
<tr>
<td>GaAsP₀.₄</td>
<td>amber</td>
<td>610</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiC</td>
<td>yellow</td>
<td>590</td>
<td>120</td>
<td>137</td>
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<tr>
<td>GaP</td>
<td>green</td>
<td>560</td>
<td>40</td>
<td>1030</td>
</tr>
<tr>
<td>InGaAlN</td>
<td>green</td>
<td>520</td>
<td>35</td>
<td>10⁷</td>
</tr>
<tr>
<td>GaN</td>
<td>blue</td>
<td>490</td>
<td></td>
<td></td>
</tr>
<tr>
<td>InGaN</td>
<td>blue</td>
<td>450 – 460</td>
<td>25</td>
<td>3 × 10⁶</td>
</tr>
<tr>
<td>InGaN</td>
<td>blue</td>
<td>400 – 430</td>
<td>20</td>
<td>3 × 10⁴</td>
</tr>
<tr>
<td>SiC</td>
<td>dark blue</td>
<td>470</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaN</td>
<td>UV</td>
<td>365 – 380</td>
<td>15</td>
<td>3 × 10⁴</td>
</tr>
</tbody>
</table>
Light Cone of LEDs

- LED without lens: Lambert source
- LED with lens: stronger forward directed beam
White Light LEDs

- Spectral broadening of LEDs to generate quasi white radiation
- Layer with phosphorescence
- Original emission in the blue
- Broad spectrum in VIS, structured
OLEDs

- The color locations are outside the sRGB / PAL / HDTV standard

Ref: K. Lindig
# Laser Source Properties

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Types</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Behavior in time</td>
<td>pulsed systems</td>
<td>solid state laser, excimer laser</td>
</tr>
<tr>
<td></td>
<td>continuous wave laser</td>
<td>HeNe-laser</td>
</tr>
<tr>
<td>Spectral width, coherence</td>
<td>single mode</td>
<td>YAG-solid state laser with high power, fiber laser, Ti:Sa-laser</td>
</tr>
<tr>
<td></td>
<td>multiple mode</td>
<td></td>
</tr>
<tr>
<td>Spectral position</td>
<td>UV</td>
<td>excimer laser</td>
</tr>
<tr>
<td></td>
<td>VIS</td>
<td>Argon-ion-laser, HeNe-laser</td>
</tr>
<tr>
<td></td>
<td>IR</td>
<td>CO₂-laser</td>
</tr>
<tr>
<td>Beam quality</td>
<td>Fundamental mode</td>
<td>HeNe-laser</td>
</tr>
<tr>
<td></td>
<td>multiple modes</td>
<td>YAG-solid state laser with high power, excimer laser</td>
</tr>
<tr>
<td></td>
<td>high NA</td>
<td>semiconductor laser</td>
</tr>
<tr>
<td></td>
<td>low NA</td>
<td>HeNe-laser, CO₂-laser</td>
</tr>
<tr>
<td></td>
<td>small diameter</td>
<td>HeNe-laser</td>
</tr>
<tr>
<td></td>
<td>large diameter</td>
<td>CO₂-laser</td>
</tr>
<tr>
<td></td>
<td>ring structures</td>
<td>CO₂-laser with unstable resonator</td>
</tr>
<tr>
<td></td>
<td>elliptical</td>
<td>excimer laser, semiconductor laser</td>
</tr>
<tr>
<td></td>
<td>astigmatic</td>
<td>semiconductor laser</td>
</tr>
<tr>
<td></td>
<td>asymmetric</td>
<td>CO₂ - waveguide laser</td>
</tr>
<tr>
<td>Power range</td>
<td>signal laser</td>
<td>HeNe-laser</td>
</tr>
<tr>
<td></td>
<td>power laser</td>
<td>CO₂-laser</td>
</tr>
<tr>
<td>Laser type</td>
<td>λ</td>
<td>Typical power / energy</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-----</td>
<td>------------------------</td>
</tr>
<tr>
<td>Excimer, ArF</td>
<td>193 nm</td>
<td>30 W / 1 J</td>
</tr>
<tr>
<td>Nitrogen-gas laser</td>
<td>337 nm</td>
<td>0.5 W / 10 mJ</td>
</tr>
<tr>
<td>Argon-ion laser</td>
<td>455 – 529 nm</td>
<td>0.5 – 20 W</td>
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<tr>
<td>HeNe-gas laser</td>
<td>632.8 nm</td>
<td>0.1 – 50 mW</td>
</tr>
<tr>
<td>HF-chemical Laser</td>
<td>2.6 – 3.3 μm</td>
<td>5 kW / 4 kJ</td>
</tr>
<tr>
<td>CO₂ – gas laser</td>
<td>10.6 μm</td>
<td>1 kW / 1 kJ</td>
</tr>
<tr>
<td>Ruby – solid state laser</td>
<td>694 nm</td>
<td>10 J</td>
</tr>
<tr>
<td>Semiconductor laser</td>
<td>0.4 – 30 μm</td>
<td>100 mW</td>
</tr>
<tr>
<td>Nd:YAG-solid state laser, flash bulb</td>
<td>1.064 μm</td>
<td>1 kW</td>
</tr>
<tr>
<td>Nd:YAG-solid state laser, diode-pumped</td>
<td>1.064 μm</td>
<td>2 W</td>
</tr>
<tr>
<td>Dye laser</td>
<td>400 – 950 nm</td>
<td>10 W / 0.1 J</td>
</tr>
</tbody>
</table>
- Gas laser with flow tube
- Brewster windows suppress reflected light
- Outcoupled radiation linear polarized

\[ r_{\parallel} = 0 \quad r_{\perp} \approx 0.4 \]
Semiconductor Laser

- Typical setup of a semiconductor laser
- Astigmatic beam radiation:
  1. fast axis perpendicular to junction
  2. slow axis parallel to junction
## Excimer Laser: Types and System Data

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>XeF</td>
<td></td>
<td>351</td>
<td>12-19</td>
<td>5.0</td>
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<tr>
<td>XeCl</td>
<td></td>
<td>308</td>
<td>11</td>
<td>4.5</td>
<td></td>
<td></td>
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<tr>
<td>XeBr</td>
<td></td>
<td>282</td>
<td>12</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KrF</td>
<td>UV</td>
<td>248</td>
<td>6.5-9</td>
<td>2.5</td>
<td>25</td>
<td>6.6 / 2.6</td>
</tr>
<tr>
<td>ArF</td>
<td>DUV</td>
<td>193</td>
<td>4.2</td>
<td>2.9</td>
<td>15</td>
<td>7.4 / 3.2</td>
</tr>
<tr>
<td>F$_2$</td>
<td>DUV</td>
<td>157</td>
<td>9</td>
<td>13.0 / 6.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ar$_2$</td>
<td>DUV</td>
<td>126</td>
<td>9</td>
<td>13.0 / 6.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Graph:**
- **Y-axis:** Intensity
- **X-axis:** Wavelength
- **Peak:** 248.5 nm
- **Line Width:**
  - Normal Laser Line: 0.3 nm
  - Narrowed Laser Line: 0.003 nm
- **Gain Line:** 2 nm
Excimer Laser: Typical Beam Profiles

Near field

Far field

157 nm

193 nm
Excimer Lasers: Spatial-Temporal Profile of Pulses

Profiles across the beam

6.4 mm
8.0 mm
3.6 mm

64 nanoseconds

Profiles across the beam

5 mrad
2.8 mrad
1.1 mrad

64 nanoseconds
Gaussian Beams, Transverse Beam Profile

- Transverse beam profile is gaussian
- Beam radius $w$ at 13.5% intensity

$$I(r) = I_o e^{-2 \left( \frac{r}{w} \right)^2}$$
- Expansion of the intensity distribution around the waist $I(r,z)$

Gaussian Beams

[Diagram showing Gaussian beams, including axes for $x$ and $z$, hyperbolic caustic curve, asymptotic lines, $w(z)$, $R(z)$, focal point $z_0$, and beam waist $w_0$.]
Caustic of a Gaussian Beam

- Intensity $I(x,z)$
Geometry of Gaussian Beams
Gaussian Beam Propagation

- Paraxial transform of a beam
- Intensity $I(x,z)$

$$I(r, z) = \frac{2P}{\pi \cdot w^2(z)} e^{-2 \left( \frac{r}{w(z)} \right)^2}$$
Illumination systems:

- Different requirements: energy transfer efficiency, uniformity
- Performance requirements usually relaxed
- Very often complicated structures components
- Problem with raytracing: a ray corresponds to a plane wave with infinity extend
- Usual method: Monte-Carlo raytrace
  Problems: statistics and noise
- Illumination systems and strange components needs often a strong link to CAD data
- There are several special software tools, which are optimized for (incoherent) illumination:
  - LightTools
  - ASAP
  - FRED
- Superposition of subapertures with different profiles
- Flip of orientation due to reflection
- Simple example:
  - Towards tophat from gaussian profile by only one reflection
- Number of reflection depends on length and incident angle

\[ m = \frac{2L \cdot \tan u'}{a} \]

- Kontrast V as a function of length
- Ideal homogenization:
  incoherent light without interference
- Parameter:
  Length $L$, diameter $d$, numerical aperture angle $\theta$, reflectivity $R$
- Partial or full coherence:
  speckle and fine structure disturbs uniformity
- Simulation with pint ssourse and lambert indicatrix or supergaussian profile

Rectangular Slab Integrator
Rectangular Slab Integrator

- Full slab integrator:
  - total internal reflection, small loss
  - small limiting aperture
  - problems high quality of end faces
  - also usable in the UV

- Hollow mirror slab:
  - cheaper
  - loss of 1-2% per reflection
  - large angles possible
  - no problems with high energy densities
  - not useful in the UV
- Array of lenslets divides the pupil in supabertures
- Every subaperture is imaged into the field plane
- Overlay of all contributions gives uniformity
- Problems with coherence: speckle
- Different geometries: square, hexagonal, triangles
- Simple setup with one array
- Improved solution with double array and additional imaging of the pupil
Example illumination fields of a homogenized gaussian profile

a) single array
b) double array
- sharper imaging of field edges
- no remaining diffraction structures
Complex Components: Fresnel Surfaces

- Non-smooth surfaces in Fresnel lenses
- Raytrace more complicated
- Example:
  - Lighthouse optics
Segmented Surfaces and Arrays

Types of surfaces:

- Mirror with facets
- Regular lenslet array
- Statistical lenslets
Conical Light Taper

- Waveguide with conical boundary
- Lagrange invariant: decrease in diameter causes increase in angle:
  Aperture transformed
  \[ D_{\text{in}} \cdot \sin u = D_{\text{out}} \cdot \sin u' \]
- Number of reflections:
  - depends on diameter/length ratio
  - defines change of aperture angle

\[ \sin u \frac{D_{\text{in}}}{2} = \sin u' \frac{D_{\text{out}}}{2} \]
Axicon Lens Combination

- Generation of a ring profile
- Axicon: cone surface with peak on axis
- Ringradius in the focal plane of the lens
  \[ R = (n - 1) \cdot f \cdot \alpha \]
- Ring width due to diffraction
  \[ \Delta R = \frac{1.22 \cdot f \cdot \lambda}{a} \]
Axicon Component

- Axicon: component with cone surface
- Refractive or reflective versions possible
- Refractive:
  - small angle approximation \[ \beta = (n - 1) \cdot \alpha \]
- Fresnel principle not fulfilled
- Benefit: extended line along axis but nonuniform peak height
Illumination Optics: Collector

- Requirements and aspects:
  1. Large collecting solid angle
  2. Correction not critical
  3. Thermal loading
     large
  4. Mostly shell-structure
     for high NA
Illumination Optics: Condenser

2. Abbe type, achromatic, $NA = 0.9$, aplanatic, residual spherical

3. Aplanatic achromatic, $NA = 0.85$
Köhler Illumination Principle

Principle of Köhler illumination:

- Alternating beam paths of field and pupil
- No source structure in image
- Light source conjugated to system pupil
- Differences between ideal and real ray paths
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
Illumination Optics: Overview

- Four possibilities for practical needs
- Epi vs. trans-illumination
- Bright vs. dark field illumination
- Comparison of light cones for imaging and illumination parts
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
2. Epi-illumination

Complicated ring-shaped components around objective lens
RXI Collimator

- Collimating highly divergent radiation of a LED
- Separation of the beam path into two channels
- Good performance of collimation only for axis point
- Good collection efficiency
Automotive Head Lamps

Historical development of automotive head lamp

- 1908: first electrical head lamp
- 1957: projection system
- 1983: Asymmetrical light distribution
- 1992: Xenon lamp
- 2002: dynamical curve light
- 2006: adaptive system
- 2008: matrix head lamp
- 2010: full LED head lamp
- 2014: static laser module
- 201X: high resolution laser and LED modules

Ref: A. Wolf
Automotive Head Lamps

Historical development of automotive head lamp

Ref: A. Wolf
LED in Automotive

- Headlamp
  - long lifetime
  - no filaments
  - better color temperature possible
  - different optical principles

- Interior

Ref.: J. Muschaweck
Comparison Imaging vs Illumination

- Imaging optics
  - point to point transfer
  - transfer of information

- Illumination
  - mapping extended source on extended target
  - imaging to be avoided
  - transfer of flux

- Comparison
  - different tasks
  - different tools
  - different methods

Ref.: J. Muschaweck
Raytube-Modell

- **Optical power flux**

- **General transfer:** Jacobian matrix of differential area transform

\[ \Delta^2 \Phi = \frac{L_j}{r_{j,j+1}^2} \cdot \cos \theta_j \cdot \cos \theta_{j+1} \cdot \Delta A_j \cdot \Delta A_{j+1} \]

\[ \Delta A' = J \cdot \Delta A \]

\[
J = \begin{vmatrix}
\frac{dx'}{dx} & \frac{dx'}{dy} \\
\frac{dy'}{dx} & \frac{dy'}{dy}
\end{vmatrix} = \frac{dx'}{dx} \cdot \frac{dy'}{dy} - \frac{dx'}{dy} \cdot \frac{dy'}{dx}
\]
- Decomposition of all surfaces into small area patches
- Modelling the light transfer between all combinations of area elements by raytubes
- Taking incidence angles into account
Illumination Simulation

- Simple raytrace: S/N depends on the number of rays $N$

- Improved SNR: raytube propagation transport of energy density
Special problems in the layout of illumination systems:
1. complex components: segmented, multi-path
2. special criteria for optimization:
   - homogeneity
   - efficiency
3. incoherent illumination: non-unique solution
3. Illumination systems, here:
   - cylindrical pump-tube of a solid state laser
   - two flash lamps (A, B) with cooling flow tubes (C, D)
   - laser rod (E) with flow tube (F, G)
   - double-elliptical mirror
     for refocussing (H)
Different ray paths possible
Beam Profiling / Overview

- **incoherent**
  - single aperture
    - geometrical transform
    - tailoring
    - edge ray principle
    - LSQ numerical
  - multiple aperture

- **coherent**
  - single aperture
    - near field
      - aspherical lens
      - bi-prism, axicon
      - geometrical transform
    - far field
      - spectrum shaping
      - phase filtering
      - holographic transform
  - multiple aperture
    - super-position
    - phase grating
    - aperture filling

- **partial coherent**
  - source integration

Rev: H.-P. Herzig
Line Focus Generation with Ringlens

- Ring lens creates ring focus
- Fourier lens generates Bessel beam of finite length
- Apodization allows for an improved uniformity
Line Focus Generation with Ringlens

- Intensity

Bessel profile $I(r)$

Intensities $I(r,z)$

Line profile $I(z)$
- Bessel beam generation by axicon optic
- Double axicon to create larger working distances
- Further finetuning of beam profile and z-uniformity by aspherical surfaces possible
- Advantage: monolithic component
- Critical: centering tolerances

### Line Focus Generation

**double axicon, asymmetric**

- $D_{in} = 7 \text{ mm}$
- $d = 1.2 \text{ mm}$
- $\sin u = 0.233$
- $5 \text{ mm free working distance}$
- $5 \text{ mm line length}$
Traditional Coherent Beam Profiling

- Classical transformation of beam profiles by aspheres
- Optional repair of phase by second asphere
- Geometries:
  1. circular symmetric (simple)
  2. general (freeforms)
Alternative way to generate a ring: spiral phase plate with intermediate twist

Setup:
- pair of spiral phase plates generate ring, twisted phase
- pair of axicons changes aspect ratio and creates focusing with large free working distance
- Bessel line focus in final plane

Advantage:
reduced alignment sensitivity of axicons
Freeform Systems: Exact Tailoring

- Basic idea of tailoring:
  - point-wise mapping of surfaces
  - fulfillment of Fermat principle
  - fulfillment of correct photometry

- Ref: Winston/Minano/Benitez, Nonimaging optics
Tailoring Method for Intensity Profiling

- Calculation of freeform shape by solution of partial differential equation
- Figures:
  1. Workpiece
  2. Contour lines of freeform surface
  3. Desired image
  4. Simulated image

Ref: H. Ries
- Optimal mass transport method
- Two-step process:
  1. Optimal mass transport mapping of points with least action principle
  2. Construction of freeform to realize this mapping
- Examples: 1. desired intensity 2. freeform surface 3. obtained result

Ref: C. Bösel
Colored Freeform Projector

- Simultaneous projection of three gaussian laser sources
- Four freeforms on one substrate
- Some problems with hard edges / high spatial frequencies

Ref: B. Satzer