Physical Optics

Lecture 8: Laser
2017-05-24
Beate Boehme

Most slides from Herbert Gross
<table>
<thead>
<tr>
<th>No</th>
<th>Date</th>
<th>Subject</th>
<th>Ref</th>
<th>Detailed Content</th>
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<tbody>
<tr>
<td>1</td>
<td>05.04</td>
<td>Wave optics</td>
<td>G</td>
<td>Complex fields, wave equation, k-vectors, interference, light propagation, interferometry</td>
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<tr>
<td>2</td>
<td>12.04</td>
<td>Diffraction</td>
<td>B</td>
<td>Slit, grating, diffraction integral, diffraction in optical systems, point spread function, aberrations</td>
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<tr>
<td>3</td>
<td>19.04</td>
<td>Fourier optics</td>
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<td>Plane wave expansion, resolution, image formation, transfer function, phase imaging</td>
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<td>4</td>
<td>26.04</td>
<td>Quality criteria and resolution</td>
<td>B</td>
<td>Rayleigh and Marechal criteria, Strehl ratio, coherence effects, two-point resolution, criteria, contrast, axial resolution, CTF</td>
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<td>5</td>
<td>03.05</td>
<td>Polarization</td>
<td>G</td>
<td>Introduction, Jones formalism, Fresnel formulas, birefringence, components</td>
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<tr>
<td>6</td>
<td>10.05</td>
<td>Photon optics</td>
<td>D</td>
<td>Energy, momentum, time-energy uncertainty, photon statistics, fluorescence, Jablonski diagram, lifetime, quantum yield, FRET</td>
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<td>7</td>
<td>17.05</td>
<td>Coherence</td>
<td>G</td>
<td>Temporal and spatial coherence, Young setup, propagation of coherence, speckle, OCT-principle</td>
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<tr>
<td>8</td>
<td>24.05</td>
<td>Laser</td>
<td>B</td>
<td>Atomic transitions, principle, resonators, modes, laser types, Q-switch, pulses, power</td>
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<tr>
<td>9</td>
<td>31.05</td>
<td>Gaussian beams</td>
<td>D</td>
<td>Basic description, propagation through optical systems, aberrations</td>
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<tr>
<td>10</td>
<td>07.06</td>
<td>Generalized beams</td>
<td>D</td>
<td>Laguerre-Gaussian beams, phase singularities, Bessel beams, Airy beams, applications in superresolution microscopy</td>
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<tr>
<td>11</td>
<td>14.06</td>
<td>PSF engineering</td>
<td>G</td>
<td>Apodization, superresolution, extended depth of focus, particle trapping, confocal PSF</td>
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<tr>
<td>12</td>
<td>21.06</td>
<td>Nonlinear optics</td>
<td>D</td>
<td>Basics of nonlinear optics, optical susceptibility, 2nd and 3rd order effects, CARS microscopy, 2 photon imaging</td>
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<tr>
<td>13</td>
<td>28.06</td>
<td>Scattering</td>
<td>G</td>
<td>Introduction, surface scattering in systems, volume scattering models, calculation schemes, tissue models, Mie Scattering</td>
</tr>
<tr>
<td>14</td>
<td>05.07</td>
<td>Miscellaneous</td>
<td>G</td>
<td>Coatings, diffractive optics, fibers</td>
</tr>
</tbody>
</table>

D = Dienerowitz    B = Böhme    G = Gross
Laser

- Introduction
- Spontaneous and Stimulated Emission
- Laser Amplifiers and Feedback
- Resonator optic
- Laser types
- Quality of laser beams
- Summary
Light Amplification by Stimulated Emission of Radiation

- Diffraction-limited beams with high intensity
- Well defined, in general narrow spectral width - monochromatic
- Spatial (lateral) and temporal (axial) coherence

Components

- **Amplifier**
  - Active medium: emission of photons by atoms or molecules
  - Stimulated emission of photons
  - Solids (crystals: ruby 1960, semiconductors, fibers, …)
  - Gases (HeNe, CO₂), fluids (dye lasers),
  - Gain saturation

- **Power supply**
  - Creation of an inverse occupation of energy levels
  - At minimum 3-energy levels with relaxation time
  - Optic or electric energy

- **Resonator**
  - Positive feedback of selected frequencies

Steady-state: gain = resonator loss
Laser – safety of radiation

- Laser warning sign: DIN EN ISO 7010
  DIN VDE 0837

  class 1: the accessible laser radiation is safe
  class 2: it’s a VIS laser (400-700nm)  
    an exposure less than 0.25s is safe for the eye (in discussion)
  class 3B: the radiation is dangerous for the eye, sometimes for skin  
    diffuse scattered light is safe
  class 4: danger for eye, tissue  
    and with scattered light

- Visible laser: eye lid closure
- Invisible laser: no lid closure,  
  often class 3B
- Classification depends on wavelength,  
  cw or pulsed exposure type and time,  
  divergence

Example: MZB for collimated cw laser

[chart showing laser intensity vs. wavelength]

https://wikimedia.org: Von Danh - Eigenes Werk, CC BY-SA 3.0
Laser

Spontaneous and Stimulated Emission

Laser amplification
Spontaneous and stimulated emission

Absorption

- Excitation of an atom to a higher energy level
  \[ E_{\text{Photon}} = h\nu = E_1 - E_2 \]
- Energy of the photon and wavelength
  \[ \lambda_{\text{photon}} = \frac{hc}{E_1 - E_2} > 90\text{nm} \]
- \[ l_a = I_0 \cdot e^{-\sigma_{12} N_Z} \]

Spontaneous emission

- Deexcitation
- Statistical process with finite life time \( \tau_{sp} \)

Stimulated emission

- Deexcitation stimulated by incoming photon
  \[ l_{st} = I_0 \cdot e^{+\sigma_{21} N_Z} \]
Equilibrium of population according to the Boltzmann distribution

\[ \frac{N_2}{N_1} = e^{\frac{E_2 - E_1}{kT}} \]

- If \( N_2 > N_1 \): inversion
- Total gain factor over a length \( z \)

\[ G = \frac{I}{I_0} = e^{g \cdot z} \]

With a two-level system it is impossible to obtain an inversion of the population, because absorption and stimulated emission have equal probability.

Ref.: M. Kaschke
3-Level System

- Three energy levels
- Inversion is only possible for strong pump rates $W$
  \[ \frac{N_2}{N_1} = W \cdot \tau_2 \]
- Non-radiative relaxation: life time $\tau_3$
- Laser level must have longer life time $\tau_2$
  \[ \tau_2 \gg \tau_3 \]
- At least 50% of the atoms must be in the upper level

Ref.: M. Kaschke
4-Level System

- Two fast non-radiative transitions
- If the relations:
  \[ \tau_4 \ll \tau_3, \quad \tau_3 \text{ large}, \quad \tau_2 \text{ small} \]
  
  are fulfilled:
  inversion of population is independent of the pump rate
  \[ \frac{N_3}{N_2} \gtrsim \frac{\tau_3}{\tau_2} \]
  
- Comfortable laser scheme

Ref.: M. Kaschke
Stationary Laser Oscillator

- **Setup**

- Laser condition: Gain at active medium > Resonator losses
- Cw-laser: gain = loss

Ref.: M. Kaschke
Axial Modes

- The mirrors are phase surfaces
- The standing wave inside the resonator must have knots at the mirrors
  \[ L = q \cdot \lambda / 2 \]
- Every integer \( q \) gives one axial mode

\[ \Delta v = c / 2L \]
Spectral distribution of amplification

- Spectral bandwidth $B$ with gain $\gamma_0(\nu) > \alpha_{\text{res}}$ loss
- Finite number of axial modes $M \sim B / \Delta \nu$
- Inhomogeneously broadened medium:
  - independent processes $\rightarrow$ multimode laser
- Homogeneously broadened medium:
  - gain saturation central modes compete with the peripheral.
  - in ideal case one mode remains, but spatial hole burning
Cw-laser and external switch: peak power ≤ cw power

\[
\begin{bmatrix}
\quad & \quad \\
\quad & \quad \\
\end{bmatrix}
\]

Internal modulation: collection of energy:

\[
\begin{bmatrix}
\quad & \quad & \quad \\
\quad & \quad & \quad \\
\end{bmatrix}
\]

Gain switching: pumping power
Q-switching = loss switching: increasing resonator losses by modulated absorption: ns
Cavity dumping: modification of mirror transmission

Mode-locking: multimode-modes are locked with their phases together
periodic pulse train with period \( T = 2L/c = \) time for single round trip
pulse width: fs, \( t = T / M = 1/ M \Delta \nu \)
- Time dependencies for cw and pulsed mode

Ref.: M. Kaschke
Mode Locking

- Fixed phase relation between modes $\Phi = \Phi_{q+1} - \Phi_q$
- Full interference of amplitudes
- Pulse corresponds to Fourier transformation $\sin (M\nu)/\sin(\nu)$

Shorter pulses for high number of modes
Repetition rate corresponds to $\Delta\nu$

Ref.: M. Kaschke
Resonator optic
Laser resonators

Planar mirror resonator

Ring resonator

Fiber resonator

Spherical mirror resonator
Laser resonators – ray description

paraxial description with matrix formalism for rays:

\[
\begin{pmatrix}
A & B \\
C & D
\end{pmatrix}
\]

\[
\begin{pmatrix}
x' \\
\alpha'
\end{pmatrix}
= \begin{pmatrix}
A & B \\
C & D
\end{pmatrix}
\begin{pmatrix}
x \\
\alpha
\end{pmatrix}
\]

Free space, distance L

\[
\begin{pmatrix}
1 & L \\
0 & 1
\end{pmatrix}
\]

Lens / mirror

\[
\begin{pmatrix}
1 & \frac{2}{R} \\
\frac{1}{f} & 1
\end{pmatrix}
\]

Grating: extension of formalism possible

\[
\begin{pmatrix}
1 \\
m\lambda g
\end{pmatrix}
\]

Stable resonator:
Conservation of rays after m periods:

\[
\begin{pmatrix}
x_m \\
\alpha_m
\end{pmatrix}
= \begin{pmatrix}
A & B \\
C & D
\end{pmatrix}^m
\begin{pmatrix}
x \\
\alpha
\end{pmatrix}
\]

Differential equation for ray parameters
Stable resonator with real solution:
Condition

\[ 0 \leq g_1 g_2 < 1 \]

\[ g_1 = 1 - \frac{L}{R_1} \quad g_2 = 1 - \frac{L}{R_2} \]

- Mirrors are phase surfaces
- \( g_1 \)-\( g_2 \) diagram of stability
- Yellow regions deliver stable operation
- Good tolerances for \( g_1, g_2 = 1/2 \)
critical configuration in the center of the stability diagram, but sensitive
One round trip creates the Fourier transform of the starting field:
due to mirror focal length is R/2
Especially good transverse mode selection
Small mode volume
stop with radius a at first mirror
beam radius @1: \( w_1 \approx a \)
beam radius @2: \( w_2 = \frac{\lambda L}{a \pi} \)
Fresnel number
resonator losses defined
Beam quality
\[ M^2 = \pi \cdot N_F \]
Reproduction of the field for one round trip: TEM00 mode, gauss mode
More general: the field inside the resonator is given by a set of eigensolutions
these are the modes of the resonator
The transverse limitations of the field due to a stop governs the modes
The eigenvalues \( g \) determine the losses of the modes (\( )\)
Hermite Gaussian Modes

Compare:
Modes of a closed box with length L
square Cross-section b

\[ \nu_{m,n,q} = \frac{c}{2} \sqrt{\left(\frac{m}{b}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{q}{L}\right)^2} \]
- circular symmetry
- Indices:
  - $p$: azimuthal
  - $l$: radial
Keplerian telescope with pinhole in focal plane

Higher modes with larger spatial extend are blocked:
- only fundamental mode transmitted, beam clean up, mode filter for higher modes laser condition not fulfilled
- Approximate size of pinhole diameter:

\[ D_{\text{P]inhole}} = \frac{2\lambda f}{\pi W_{\text{in}}} = 0.637 \cdot \frac{\lambda f}{W_{\text{in}}} \]

More general: Increase off losses for higher modes
- Diameter of active material
- Pinhole at minimum beam diameter
- Small Fresnel number \( N_F = \frac{a^2}{\lambda L} \) Long resonators
- High power lasers: instable resonators
- Types of lasers:
  - Ar laser
  - CO₂ laser
  - YAG laser
  - disc laser
  - fiber laser
  - semiconductor laser
  - Excimer laser

- Beam quality of lasers
<table>
<thead>
<tr>
<th>Type</th>
<th>λ</th>
<th>Power</th>
<th>Mode</th>
<th>Puls-length</th>
<th>Beam Dia. mm</th>
<th>Full Divergence mrad</th>
<th>Efficiency η %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Excimer, ArF</strong></td>
<td>193 nm</td>
<td>30 W</td>
<td>Puls</td>
<td>20 ns</td>
<td>6x20 - 20x30</td>
<td>2 - 6</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Nitrogen gas</strong></td>
<td>337 nm</td>
<td>0.5 W</td>
<td>Puls</td>
<td>0.5-5 ns</td>
<td>2x3 - 6x30</td>
<td>1-3x7</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Argonionen</strong></td>
<td>505 nm</td>
<td>20 W</td>
<td>cw</td>
<td></td>
<td>0.7 - 2</td>
<td>0.4-1.5</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>HeNe agas</strong></td>
<td>632 nm</td>
<td>0.1 - 50 mW</td>
<td>cw</td>
<td></td>
<td>0.5 - 2</td>
<td>0.5 - 1.7</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>HF-Chemical</strong></td>
<td>2.7 - 3.3 μm</td>
<td>150 W</td>
<td>cw oder Pulsl</td>
<td>1 μs</td>
<td>2 - 40</td>
<td>1 - 15</td>
<td>10</td>
</tr>
<tr>
<td><strong>CO₂ – Gas</strong></td>
<td>10.6 μm</td>
<td>10 kW</td>
<td>cw oder Pulsl</td>
<td>3 - 4</td>
<td></td>
<td>1 - 2</td>
<td>5 - 30</td>
</tr>
<tr>
<td><strong>Rubin Solid State</strong></td>
<td>694 nm</td>
<td></td>
<td>Puls</td>
<td>0.5 ms</td>
<td>1.5 - 25</td>
<td>0.2 - 10</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Semiconductor</strong></td>
<td>0.4 - 30 μm</td>
<td>100 mW</td>
<td>cw oder Pulsl</td>
<td>5 ps</td>
<td>200 x 600</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td><strong>Nd:YAG Solid State, with Flash lamp</strong></td>
<td>1.064 μm</td>
<td>1 kW</td>
<td>Puls</td>
<td>5 ms - 10 ns</td>
<td>0.75 - 6</td>
<td>2 - 18</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Nd:YAG Solid State with Diode-pumped</strong></td>
<td>1.064 μm</td>
<td>2 W</td>
<td>cw</td>
<td></td>
<td>0.75 - 6</td>
<td>2 - 18</td>
<td></td>
</tr>
<tr>
<td><strong>Dye fluid</strong></td>
<td>400 - 950 nm</td>
<td>10 W</td>
<td>cw oder Pulsl</td>
<td></td>
<td>0.4 - 0.6</td>
<td>1 - 2</td>
<td>20</td>
</tr>
</tbody>
</table>
- Gas laser with flow tube
- Brewster windows suppress reflected light
- Outcoupled radiation linear polarized

\[ r_\parallel = 0 \quad r_\perp \approx 0.4 \]
Argon Laser

- Energy scheme

Ref.: M. Kaschke

\[ \lambda = 267.4 \, \text{nm} \ldots \, 528.7 \, \text{nm} \]
Argon Laser

- Setup

Two elastic strikes are necessary for excitation
1. ionization
2. excitation of upper laser level

- Efficiency low: < 0.1 %
- Output power typical: 10 W
- Wavelengths: 488 nm or 514 nm

Ref.: M. Kaschke
**CO₂ Laser**

- Atoms in electrical ground level - Laser transitions correspond to rotations and vibrations
- Oscillations of the laser energies:
  1. asymmetric stretching, upper level
  2. symmetrical stretching, lower level
  3. bending, lower level

- Energy scheme:
- Additional gases:
  N₂: excitation by collisions of 2nd kind
  He: de-excitation of lower levels

- Infrared wavelength ranges
- High efficiency:
  - cw mode: 30% and 100 kW
  - pulsed mode: 100 kJ

Ref.: M. Kaschke
Nd:YAG Laser

- Typical setup of a flash lamp pumped solid state Nd:YAG laser resonator

![Diagram of laser resonator with labeled parts: Laser beam, water cooling, Laser rod, outcoupling mirror, pump chamber, flash lamp, HR mirror.]

- Typical pump cavity of solid state lasers: coaxial rods
  - a) elliptic reflector
  - b) diffuse scattering and oval shape

Ref.: M. Kaschke
Nd:YAG Laser

- Energy scheme of an Nd:YAG laser

Ref.: M. Kaschke
Diode Pumped Solid State Lasers

- Transversal pumping geometry
- Quality problems due to
  - astigmatism and coma by broken symmetry
  - birefringence
  - thermal lensing

Ref.: M. Kaschke
- Longitudinal pumping geometry
- Usually good mode quality due to coaxial gain distribution
Disc Laser

- Extrem aspect ratio of the laser rod:
  - very thin disc (< 1mm)
  - large diameter

- Advantage:
  - no thermal lensing
  - effective cooling from front side

- Complicated:
  Pump geometry, skew incident beams

Ref.: M. Kaschke
Fiber Laser

- Basic idea: fiber core with active medium
  - propagation of pump and laser light
  - mode confinement inside the fiber, defines beam quality
  - good dissipation of heat

- Si / Phosphat / Fluorid-Glas-fiber: losses < 3dB/km
- Core doped with rare earths
- Single mode for rare earths
  - $V < 2.4$
  - $V = 2\pi \frac{r_{core}}{\lambda} \sqrt{n_{core}^2 - n_{clad}^2}$
  - $r_{core} \sim 6\mu m$ for VIS
  - $= 2\pi \frac{r_{core}}{\lambda} NA$
- Double-glad fibers for pump light
- Absorption and emission linewidth broadened to 15nm typ, caused by interaction with glass

<table>
<thead>
<tr>
<th>Dope</th>
<th>λ nm</th>
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<tr>
<td>Er</td>
<td>3400</td>
</tr>
<tr>
<td>Nd</td>
<td>1340</td>
</tr>
<tr>
<td>Yb</td>
<td>975</td>
</tr>
<tr>
<td>Tm</td>
<td>800</td>
</tr>
<tr>
<td>Pr</td>
<td>635</td>
</tr>
<tr>
<td>Er</td>
<td>546</td>
</tr>
<tr>
<td>Tm</td>
<td>455</td>
</tr>
</tbody>
</table>
Fiber Laser

- Interesting wavelength ranges for fiber lasers

Ref.: O. Okhotnikov
Fiber laser

Double glad fibers → Coupling for pump light increased reduced tolerance sensitivity

![Diagram showing fiber structure with labels for laser core DM ~ 5µm, pump core DM ~ 400µm, and gladding.]

Increase of pump light absorption by Kidney bending

![Graph showing absorption percentage against fiber length for different kidney and coiled configurations.]

Fiber Laser

- Increase of pump light absorption
  - Bending or Broken symmetry
- Max 100W cw
- Limited by nonlinear effects

- PCF = photonic crystal fibers
- Microstructures (holes) simulate reduced n, $\Delta n \sim 10e^{-4}$
- Single mode for For
  \[ V = 2\pi \frac{\Lambda}{\lambda} NA < \pi \]
- Max 2000W

Ref.: Thünnermann / O. Okhotnikov
Example for active q-switched fiber laser
Acousto-optical modulator: 1. diffraction order coupled back
- Typical setup of a semiconductor laser
- Astigmatic beam radiation:
  1. fast axis perpendicular to junction
  2. slow axis parallel to junction
- Typical spectral widths: IR greater than deep blue
- Spectral position depends on material

### Semiconductor Diodes: Spectra

<table>
<thead>
<tr>
<th>Material</th>
<th>Color</th>
<th>Wavelength in nm</th>
<th>Spectral FWHM nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAsP</td>
<td>NIR</td>
<td>1500 - 1300</td>
<td>50-150</td>
</tr>
<tr>
<td>GaAs:Si</td>
<td>NIR</td>
<td>940</td>
<td></td>
</tr>
<tr>
<td>GaAs:Zn</td>
<td>NIR</td>
<td>900</td>
<td>40</td>
</tr>
<tr>
<td>GaAlAs</td>
<td>NIR</td>
<td>880</td>
<td>30-60</td>
</tr>
<tr>
<td>GaP:Zn,N</td>
<td>dark red</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>GaP</td>
<td>red</td>
<td>690</td>
<td>90</td>
</tr>
<tr>
<td>GaAlAs</td>
<td>red</td>
<td>660</td>
<td></td>
</tr>
<tr>
<td>GaAs$_6$P$_4$</td>
<td>red</td>
<td>660</td>
<td>40</td>
</tr>
<tr>
<td>GaAs$<em>{0.35}$P$</em>{0.65}$:N</td>
<td>orange</td>
<td>630</td>
<td></td>
</tr>
<tr>
<td>InGaAlP</td>
<td>orange</td>
<td>618</td>
<td>20</td>
</tr>
<tr>
<td>GaAsP$_{0.4}$</td>
<td>amber</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>SiC</td>
<td>yellow</td>
<td>590</td>
<td>120</td>
</tr>
<tr>
<td>GaP</td>
<td>green</td>
<td>560</td>
<td>40</td>
</tr>
<tr>
<td>InGaAlN</td>
<td>green</td>
<td>520</td>
<td>35</td>
</tr>
<tr>
<td>GaN</td>
<td>blue</td>
<td>490</td>
<td></td>
</tr>
<tr>
<td>InGaN</td>
<td>blue</td>
<td>450-460</td>
<td>25</td>
</tr>
<tr>
<td>InGaN</td>
<td>blue</td>
<td>400-430</td>
<td>20</td>
</tr>
<tr>
<td>SiC</td>
<td>deep blue</td>
<td>470</td>
<td></td>
</tr>
</tbody>
</table>
Semiconductor Laser

- Typical laser with housing

- Continuous transition from incoherent LED below threshold to coherent laser above threshold

Ref: M. Kaschke
Usual semiconductor lasers:
- edge emitter, small elliptical emitter surface
- astigmatic beam form

VCSEL-Laser:
- Emission perpendicular to pn-junction
- area typical $D < 10 \, \mu m$
- Good beam quality, monomod
- Power scaling by area size possible

Demonstrated powers
Ref.: O. Okhotnikov
## Excimer Laser: Types and System Data

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>XeF</td>
<td></td>
<td>351</td>
<td>12 - 19</td>
<td>5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XeCl</td>
<td></td>
<td>308</td>
<td>11</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<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>F₂</td>
<td>DUV</td>
<td>157</td>
<td></td>
<td></td>
<td>12</td>
<td>11.0 / 4.8</td>
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<tr>
<td>Ar₂</td>
<td>DUV</td>
<td>126</td>
<td></td>
<td></td>
<td>9</td>
<td>13.0 / 6.0</td>
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</tbody>
</table>

**Images:**
- **193nm:** Near field and far field images.
- **157nm:** Near field and far field images.
Typical setup
- gas tube with Brewster windows
- rectangular aperture
- outcoupling mirror
- Line narrowing elements:

Etalon

Grating,
Also as
outcoupler
Typical Setup and Spectral Narrowing in Excimer Laser

Prism and grating:

Real example for Littrow setup
- Spectral line width of a 248 nm Excimer laser
- Typical double line of the gain with distance 0.5 nm
- Selected and narrowed by dispersive elements in the resonator
Excimer Lasers: Spatial-Temporal Profile of Pulses

Profiles across the beam:
- 8.0 mm (8.0 mm)
- 3.6 mm (3.6 mm)
- 6.4 mm (6.4 mm)

Profiles across the beam:
- 2.8 mrad (2.8 mrad)
- 1.1 mrad (1.1 mrad)
- 5 mrad (5 mrad)

64 nanoseconds (64 nanoseconds)
Conventional criteria of imaging systems are nor useful for laser beams:
1. significant apodization
2. no imaging application
3. status of coherence may be complicated

Description of the complex fields by moments of second order:
1. spatial moments of intensity profile
   second moments describes beam width
   third moment describes asymmetry
2. angular moment of the direction distribution
   second moment describes the divergence

Alternative descriptions of impuls:
1. angle \( u_x \)
2. spatial frequency \( v_x \)
3. transverse wavenumber \( k_x \)

Mixed moments: description of twist effects

\[
\langle x^m \rangle = \frac{\iint x^m |E(x, y)|^2 \, dx \, dy}{\iint |E(x, y)|^2 \, dx \, dy}
\]

\[
\langle \phi^m \rangle = \frac{\iint \phi^m |E(\phi, \psi)|^2 \, d\phi \, d\psi}{\iint |E(\phi, \psi)|^2 \, d\phi \, d\psi}
\]

\[
\begin{align*}
u_x &= v_x = \frac{k_x}{k_o} \\
u_x &= \theta_x = \lambda \cdot \frac{k_x}{k_o}
\end{align*}
\]
Quality of Laser Beams: $M^2$

- Characterizing beam quality $M^2$

- Special case: definition in waist plane

- Properties of $M^2$:
  1. Gaussian beam TEM00: $M^2 = 1$
     Smallest possible value
  2. Paraxial optical systems: $M^2$ remains constant for propagation
  3. Real beams: $M^2 > 1$ describes the decrease in quality and focussability relative to a gaussian beam

- Reasons for degradation of beam quality:
  1. intensity profile
  2. phase perturbation
  3. finite degree of coherence

- Incoherent mixture of modes: additive composition of $M^2$

- General beams: components and mixed terms

\[
M_x^2 = \frac{\pi}{\lambda} \sqrt{\langle w_x^2 \rangle \langle \theta_x^2 \rangle - \langle w_x \theta_x \rangle^2}
\]

\[
M_x^2 = \frac{\pi}{\lambda} w_{ox} \theta_x
\]

\[
M^2 = \sqrt{\frac{1}{2} \left[ (M_x^4 + M_y^4) - M_{xy}^4 \right]}
\]
- Hermite-Gauß modes
  \[ M^2 = n + m + 1 \]
- Laguerre-Gauß modes
  \[ M^2 = 2p + m + 1 \]
- Incoherent mixture of modes
  \[ M^2 = \sum_n g_{nm} (n + m + 1) \]
  \[ M^2 = \sqrt{1 + \left( \frac{w_o}{L_c} \right)^2} \]
- Gauß-Schell-Beam
  \[ M^2 = \sqrt{1 + \left( \frac{w_o}{L_c} \right)^2 + \left( \frac{w_o^2 \eta}{2L_c^2} \right)^2} \]
- Gauß-Schell-Beam with Twist
- Beam quality of high-power lasers: space bandwidth product $L_w$
- Typical M2 grows with power
<table>
<thead>
<tr>
<th>Criterion</th>
<th>Types</th>
<th>Examples</th>
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<td>Behavior in time</td>
<td>pulsed systems</td>
<td>solid state laser, excimer laser</td>
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<td>continuous wave</td>
<td>HeNe-laser</td>
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<td>laser</td>
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<td>Spectral width, coherence</td>
<td>single mode</td>
<td>HeNe-laser</td>
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<td>multiple mode</td>
<td>YAG-solid state laser with high power, fiber laser, Ti:Sa-laser</td>
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<td>Spectral position</td>
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<td>Argon-ion-laser, HeNe-laser CO₂-laser</td>
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<td>Beam quality</td>
<td>Fundamental mode</td>
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<td>multiple modes</td>
<td>YAG-solid state laser with high power, excimer laser</td>
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<td>Beam shape</td>
<td>high NA</td>
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<td>low NA</td>
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<td>small diameter</td>
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<tr>
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<td>large diameter</td>
<td>CO₂-laser</td>
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<td>CO₂-laser with unstable resonator</td>
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<td>signal laser</td>
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<tr>
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<td>power laser</td>
<td>CO₂-laser</td>
</tr>
</tbody>
</table>
Properties of Laser Light and Consequences

- **Spectral bandwidth** very narrow
  - quasi monochromatic

- **Coherence** very high
  - in case of monomode beam perfect
  - ideal for interferometric applications
  - creates speckle

- **Power density** very high
  - in multimodes sometimes hotspots in the profile
  - heating of components
  - damage of coatings possible

- **Stability** low due to non-linear system
  - a change of laser power may cause changes of beam modes

- **Beam profile** characteristic gaussian shapes
  - beam quality criteria hard to define
  - aperture not clearly defined

- **Space-bandwidth product**
  - very low
  - for monomodes diffraction limited