WORCESTER POLYTECHNIC INSTITUTE
MECHANICAL ENGINEERING DEPARTMENT

Optical Metrology and NDT
ME-593 / ME-5304, C’2019

Lecture 02
January 2019
Light Sources
Electromagnetic spectrum

Penetrates Earth’s Atmosphere?

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Microwave</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Infrared</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Visible</td>
<td>$0.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>X-ray</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Gamma ray</td>
<td>$10^{-12}$</td>
</tr>
</tbody>
</table>

Approximate Scale of Wavelength:
- Buildings
- Humans
- Butterflies
- Needle Point
- Protozoans
- Molecules
- Atoms
- Atomic Nuclei

Frequency (Hz):
- $10^4$
- $10^8$
- $10^{12}$
- $10^{15}$
- $10^{18}$
- $10^{18}$
- $10^{20}$

Temperature of objects at which this radiation is the most intense wavelength emitted:
- 1 K: $-272 ^\circ C$
- 100 K: $-173 ^\circ C$
- 10,000 K: 9,727 °C
- 10,000,000 K: ~10,000,000 °C

THE VISIBLE SPECTRUM - Wavelength in Nanometers

400 (Ultra Violet) 450 Blue 500 Cyan 550 Green 600 Yellow 650 Orange 700 Red 750 (infra)
Light Sources
Electromagnetic spectrum

THE VISIBLE SPECTRUM - Wavelength in Nanometers

- 400 (ultra) Violet
- 450 Blue
- 500 Cyan
- 550 Green
- 600 Yellow
- 650 Orange
- 700 Red
- 750 (infra)
Light Sources
Collection and collimation

Lens: collecting and collimating light from a source

\[ F\# \approx \frac{f}{D} \quad \text{N.A.} \approx \sin \theta \]
Light Sources
Reflectors

Parabolic reflectors
Light Sources
Reflectors

Ellipsoidal reflectors
Light Sources

Irradiance

Light collection by a lens at three different distances from a source:

1. **Collimated Beam**
   - TOTAL ENERGY = $\phi$

2. **Divergent Beam**
   - TOTAL ENERGY = $4\phi$

3. **Convergent Beam**
   - TOTAL ENERGY = $.25\phi$
Lambert’s Cosine Law holds that the radiation per unit solid angle (the radiant intensity) from a flat surface varies with the cosine of the angle to the surface normal.

\[ I_\theta = I_0 \cos \theta \text{ Wsr}^{-1} \]
# Light Sources

## Irradiance

### Commonly used Radiometric, Photometric, and Photon quantities

<table>
<thead>
<tr>
<th>Radiometric</th>
<th>Photometric</th>
<th>Photon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>Usual Symbol</td>
<td>Units</td>
</tr>
<tr>
<td>Radiant Energy</td>
<td>$Q_e$</td>
<td>J</td>
</tr>
<tr>
<td>Radiant Power or Flux</td>
<td>$\phi_e$</td>
<td>W</td>
</tr>
<tr>
<td>Radiant Exitance or Emittance</td>
<td>$M_e$</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>Irradiance</td>
<td>$E_e$</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>Radiant Intensity</td>
<td>$I_e$</td>
<td>W sr$^{-1}$</td>
</tr>
<tr>
<td>Radiance</td>
<td>$L_e$</td>
<td>W sr$^{-1}$ m$^{-2}$</td>
</tr>
</tbody>
</table>

* Photon quantities are expressed in number of photons followed by the units, e.g. photon flux (number of photons) s$^{-1}$. The unit for photon energy is number of photons.

The subscripts $e, v,$ and $p$ designate radiometric, photometric, and photon quantities respectively. They are usually omitted when working with only one type of quantity.

**Symbols Key:**

- J: joule
- lm: lumen
- W: watts
- s: second
- m: meter
- cd: candela
- sr: steradian
- lx: lux, lumen m$^{-2}$
Light Sources

Irradiance

Setup for radiometric measurements
Light Sources
Irradiance

Typical monochromators
Light Sources
Irradiance

6426 and 6427 Xenon Flashlamps, with 68826 Power Supply.

Graph showing irradiance at 0.5 m as a function of wavelength (nm). Two lines are plotted:
- 75 W CONTINUOUS ARC LAMP
- 6427 FLASHLAMP RUNNING AT 60 Hz WITH THE 68826 POWER SUPPLY
Light Sources

Pulsed source

Typical single pulse

Typical pulsetrain display. The repetition rate shown is 100 Hz, the peak power 4 kW.
Light Sources

Arc Lamps

Spectral irradiance of various Arc Lamps
Light Sources
Light emitting diode (LED)

When a light-emitting diode is forward biased (switched on), electrons are able to recombine with electron holes within the device, releasing energy in the form of photons.

An LED consists of a chip of semiconducting material doped with impurities to create a p-n junction.
Light Sources
Light emitting diode (LED)

The wavelength of the light emitted, and thus its color depends on the band gap energy of the materials forming the p-n junction...
# Light Sources

## Light emitting diode (LED)

<table>
<thead>
<tr>
<th>Color</th>
<th>Wavelength [nm]</th>
<th>Voltage [V]</th>
<th>Semiconductor material</th>
</tr>
</thead>
</table>
| Infrared| $\lambda > 760$ | $\Delta V < 1.9$ | Gallium arsenide (GaAs)  
Aluminium gallium arsenide (AlGaAs) |
| Red     | $610 < \lambda < 760$ | $1.63 < \Delta V < 2.03$ | Aluminium gallium arsenide (AlGaAs)  
Gallium arsenide phosphide (GaAsP)  
Aluminium gallium indium phosphide (AlGaInP)  
Gallium(III) phosphide (GaP) |
| Orange  | $590 < \lambda < 610$ | $2.03 < \Delta V < 2.10$ | Gallium arsenide phosphide (GaAsP)  
Aluminium gallium indium phosphide (AlGaInP)  
Gallium(III) phosphide (GaP) |
| Yellow  | $570 < \lambda < 590$ | $2.10 < \Delta V < 2.18$ | Gallium arsenide phosphide (GaAsP)  
Aluminium gallium indium phosphide (AlGaInP)  
Gallium(III) phosphide (GaP) |
| Green   | $500 < \lambda < 570$ | $1.9^{[46]} < \Delta V < 4.0$ | Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN)  
Gallium(III) phosphide (GaP)  
Aluminium gallium indium phosphide (AlGaInP)  
Aluminium gallium phosphide (AlGaP) |
| Blue    | $450 < \lambda < 500$ | $2.48 < \Delta V < 3.7$ | Zinc selenide (ZnSe)  
Indium gallium nitride (InGaN)  
Silicon carbide (SiC) as substrate  
Silicon (Si) as substrate – (under development) |
| Violet  | $400 < \lambda < 450$ | $2.76 < \Delta V < 4.0$ | Indium gallium nitride (InGaN) |
| Purple  | multiple types | $2.48 < \Delta V < 3.7$ | Dual blue/red LEDs, blue with red phosphor, or white with purple plastic |
| Ultraviolet | $\lambda < 400$ | $3.1 < \Delta V < 4.4$ | Diamond (235 nm)$^{[47]}$  
Boron nitride (215 nm)$^{[48][49]}$  
Aluminium nitride (AlN) (210 nm)$^{[50]}$  
Aluminium gallium nitride (AlGaN)  
Aluminium gallium indium nitride (AlGaInN) – (down to 210 nm) |
| White   | Broad spectrum | $\Delta V = 3.5$ | Blue/UV diode with yellow phosphor |
Light Sources
Light emitting diode (LED)

Simultaneous wavelengths emission
Light Sources
Light emitting diode (LED)

Typical emission flux

40 Degrees

LED
Light Sources
Gas lasers: He-Ne

Schematic diagram of a He-Ne laser

Energy level diagram of a He-Ne laser
Light Sources
Gas lasers: He-Ne

He-Ne laser

Wavelength at a fundamental resonance frequency: He-Ne

632.8 nm
Light Sources
Transversal profile

He-Ne cross section of intensity

Gaussian intensity distribution

Section A-A

E amplitude of electric field [V/m]

intensity [W/m²]

position x
Light Sources
Beam diameter: focused beam

Focused beam

Input beam

Gaussian beam width

\[ w(z) = w_0 \sqrt{1 + \left( \frac{z}{z_R} \right)^2} \]

- \( w(z) \): beam waist
- \( b \): depth of focus
- \( z_R \): Rayleigh range
- \( \Theta \): total angular spread
Light Sources

Collimation and expansion of a laser beam

Beam collimation

Beam expansion
# Light Sources

**Lasers: gas**

<table>
<thead>
<tr>
<th>Laser gain medium and type</th>
<th>Operation wavelength(s)</th>
<th>Pump source</th>
<th>Applications and notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium-neon laser</td>
<td>632.8 nm (543.5 nm, 583.9 nm, 611.8 nm, 1.1523 µm, 1.52 µm, 3.3913 µm)</td>
<td>Electrical discharge</td>
<td>Interferometry, holography, spectroscopy, barcode scanning, alignment, optical demonstrations.</td>
</tr>
<tr>
<td>Argon laser</td>
<td>454.8 nm, 488.0 nm, 514.5 nm (351 nm, 363.8, 457.9 nm, 466.8 nm, 476.5 nm, 472.7 nm, 528.7 nm, also frequency doubled to provide 244 nm, 257 nm)</td>
<td>Electrical discharge</td>
<td>Retinal phototherapy (for diabetes), lithography, confocal microscopy, spectroscopy pumping other lasers.</td>
</tr>
<tr>
<td>Krypton laser</td>
<td>416 nm, 530.9 nm, 568.2 nm, 647.1 nm, 676.4 nm, 752.5 nm, 799.3 nm</td>
<td>Electrical discharge</td>
<td>Scientific research, mixed with argon to create &quot;white-light&quot; lasers, light shows.</td>
</tr>
<tr>
<td>Xenon ion laser</td>
<td>Many lines throughout visible spectrum extending into the UV and IR.</td>
<td>Electrical discharge</td>
<td>Scientific research.</td>
</tr>
<tr>
<td>Nitrogen laser</td>
<td>337.1 nm</td>
<td>Electrical discharge</td>
<td>Pumping of dye lasers, measuring air pollution, scientific research. Nitrogen lasers can operate superradiantly (without a resonator cavity). Amateur laser construction. See TEA laser</td>
</tr>
<tr>
<td>Carbon dioxide laser</td>
<td>10.6 µm, (9.4 µm)</td>
<td>Transverse (high power) or longitudinal (low power) electrical discharge</td>
<td>Material processing (cutting, welding, etc.), surgery.</td>
</tr>
<tr>
<td>Carbon monoxide laser</td>
<td>2.6 to 4 µm, 4.8 to 8.3 µm</td>
<td>Electrical discharge</td>
<td>Material processing (engraving, welding, etc.), photoacoustic spectroscopy.</td>
</tr>
<tr>
<td>Excimer laser</td>
<td>193 nm (ArF), 248 nm (KrF), 308 nm (XeCl), 353 nm (XeF)</td>
<td>Excimer recombination via electrical discharge</td>
<td>Ultraviolet lithography for semiconductor manufacturing, laser surgery, LASIK.</td>
</tr>
</tbody>
</table>
Light Sources
Laser diodes: semiconductors

Laser diodes: package and semiconductor dyes
Light Sources
Laser diodes: semiconductors

Diagram of front view of a double heterostructure laser diode

Diagram of a simple vertical-cavity surface emitting laser (VCSEL) structure

Elliptical output profile of intensity
Light Sources
Laser diodes: semiconductors

Elliptical output profile of intensity

Cylindrical microlens for laser diode beam correction

Anamorphic prisms for laser diode beam correction
## Light Sources

### Laser diodes: semiconductors

<table>
<thead>
<tr>
<th>Laser gain medium and type</th>
<th>Operation wavelength(s)</th>
<th>Pump source</th>
<th>Applications and notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Semiconductor laser diode (general information)</strong></td>
<td>0.4-20 µm, depending on active region material.</td>
<td>Electrical current</td>
<td>Telecommunications, holography, printing, weapons, machining, welding, pump sources for other lasers.</td>
</tr>
<tr>
<td>GaN</td>
<td>0.4 µm</td>
<td></td>
<td>Optical discs. 405 nm is used in Blu-Ray discs reading/recording.</td>
</tr>
<tr>
<td>AlGaInP, AlGaAs</td>
<td>0.63-0.9 µm</td>
<td></td>
<td>Optical discs, laser pointers, data communications. 780 nm Compact Disc, 650 nm general DVD player and 635 nm DVD for Authoring recorder laser are the most common lasers type in the world. Solid-state laser pumping, machining, medical.</td>
</tr>
<tr>
<td>InGaAsP</td>
<td>1.0-2.1 µm</td>
<td></td>
<td>Telecommunications, solid-state laser pumping, machining, medical.</td>
</tr>
<tr>
<td>lead salt</td>
<td>3-20 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vertical cavity surface emitting laser (VCSEL)</strong></td>
<td>850 - 1500 nm, depending on material</td>
<td></td>
<td>Telecommunications</td>
</tr>
<tr>
<td>Quantum cascade laser</td>
<td>Mid-infrared to far-infrared.</td>
<td></td>
<td>Research, Future applications may include collision-avoidance radar, industrial-process control and medical diagnostics such as breath analyzers.</td>
</tr>
<tr>
<td>Hybrid silicon laser</td>
<td>Mid-infrared</td>
<td></td>
<td>Research</td>
</tr>
</tbody>
</table>
Light Sources

Solid state lasers

Nd:YAG laser used as an optical pump

Neodymium-doped glass rod
Light Sources
Solid state lasers: Ruby laser - first visible laser invented

Synthetic ruby crystal used as gain medium

Theodore Maiman, 1960
## Light Sources
### Solid state lasers

<table>
<thead>
<tr>
<th>Laser gain medium and type</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Ruby laser</strong></td>
<td>694.3 nm</td>
<td>Flashlamp</td>
<td>Holography, tattoo removal. The first type of visible light laser invented; May 1960.</td>
</tr>
<tr>
<td><strong>Nd:YAG laser</strong></td>
<td>1.064 μm, (1.32 μm)</td>
<td>Flashlamp, laser diode</td>
<td>Material processing, rangefinding, laser target designation, surgery, research, pumping other lasers (combined with frequency doubling to produce a green 532 nm beam). One of the most common high power lasers. Usually pulsed (down to fractions of a nanosecond)</td>
</tr>
<tr>
<td><strong>Er:YAG laser</strong></td>
<td>2.94 μm</td>
<td>Flashlamp, laser diode</td>
<td>Periodontal scaling, Dentistry</td>
</tr>
<tr>
<td><strong>Neodymium YLF (Nd:YLF) solid-state laser</strong></td>
<td>1.047 and 1.053 μm</td>
<td>Flashlamp, laser diode</td>
<td>Mostly used for pulsed pumping of certain types of pulsed Ti:sapphire lasers, combined with frequency doubling.</td>
</tr>
<tr>
<td><strong>Neodymium doped Yttrium orthovanadate (Nd:YVO₄) laser</strong></td>
<td>1.064 μm</td>
<td>Laser diode</td>
<td>Mostly used for continuous pumping of mode-locked Ti:sapphire or dye lasers, in combination with frequency doubling. Also used pulsed for marking and micromachining. A frequency doubled nd:YVO₄ laser is also the normal way of making a green laser pointer.</td>
</tr>
<tr>
<td><strong>Neodymium doped yttrium calcium oxoborate Nd:YCa₄O (BO₃)₃ or simply Nd:YCOB</strong></td>
<td>~1.060 μm (~530 nm at second harmonic)</td>
<td>Laser diode</td>
<td>Nd:YCOB is a so called &quot;self-frequency doubling&quot; or SFD laser material which is both capable of lasing and which has nonlinear characteristics suitable for second harmonic generation. Such materials have the potential to simplify the design of high brightness green lasers.</td>
</tr>
<tr>
<td><strong>Neodymium glass (Nd:Glass) laser</strong></td>
<td>~1.062 μm (Silicate glasses), ~1.054 μm (Phosphate)</td>
<td>Flashlamp, laser diode</td>
<td>Used in extremely high power (terawatt scale), high energy (megajoules) multiple beam systems for inertial confinement fusion. Nd:Glass lasers are usually frequency tripled to the</td>
</tr>
</tbody>
</table>
Light Sources
Semiconductor, tunable lasers

Modified Littman-Metcalf configuration (external cavity)

Typical power output
Announcements

• Next class: project for this class; list of topics (CF) and teams (Students)

• Laboratory visit(s) – after class today/next class

Assignment, due next lecture:

a) Reading: Chapter 2 of Yoshizawa: Lenses/Prisms/Mirrors

b) Homework: Problems Ch02 - see website of our course