# WORCESTER POLYTECHNIC INSTITUTE
## MECHANICAL ENGINEERING DEPARTMENT

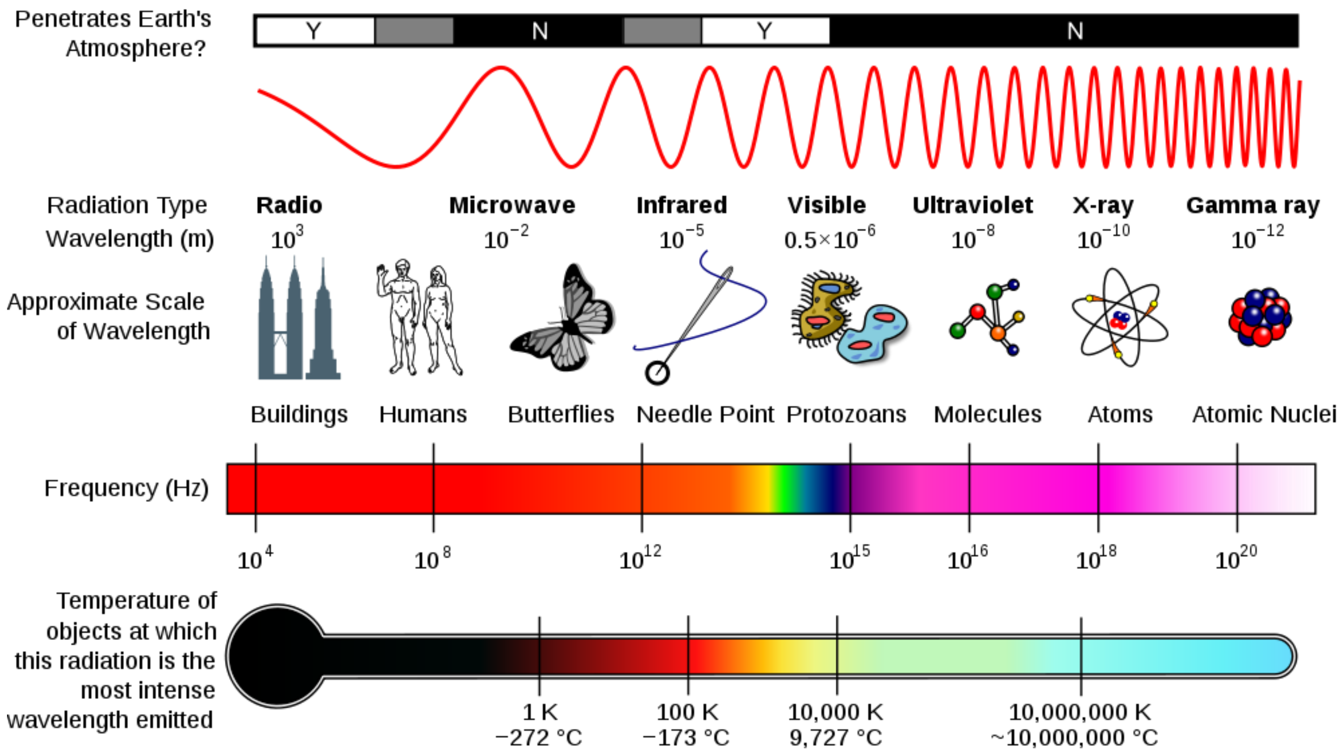
**Optical Metrology and NDT**
**ME-593 / ME-5304, C'2025**

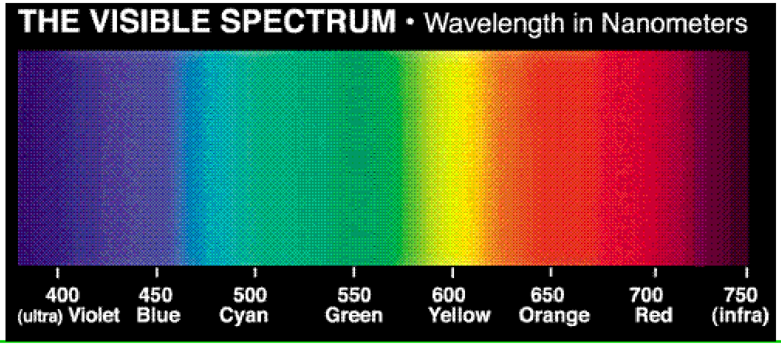
**Lecture 02**

**January 2025**

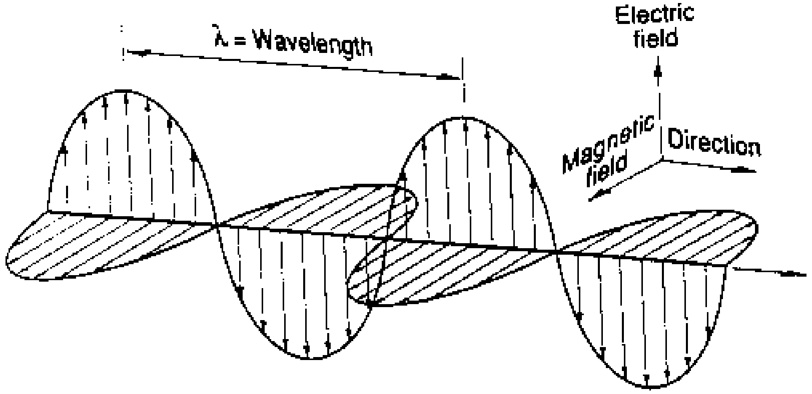
# Light Sources

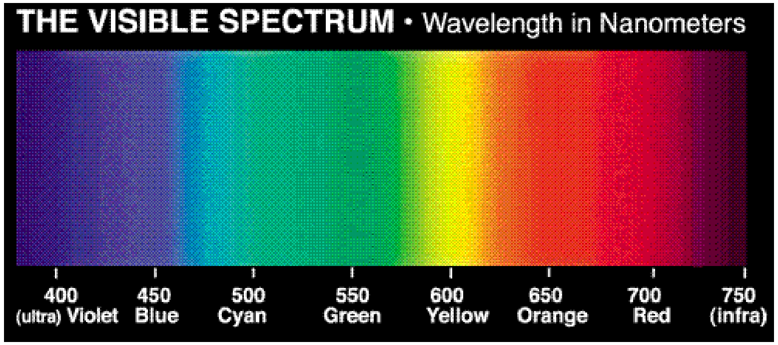
## Electromagnetic spectrum



# Light Sources
## Electromagnetic spectrum

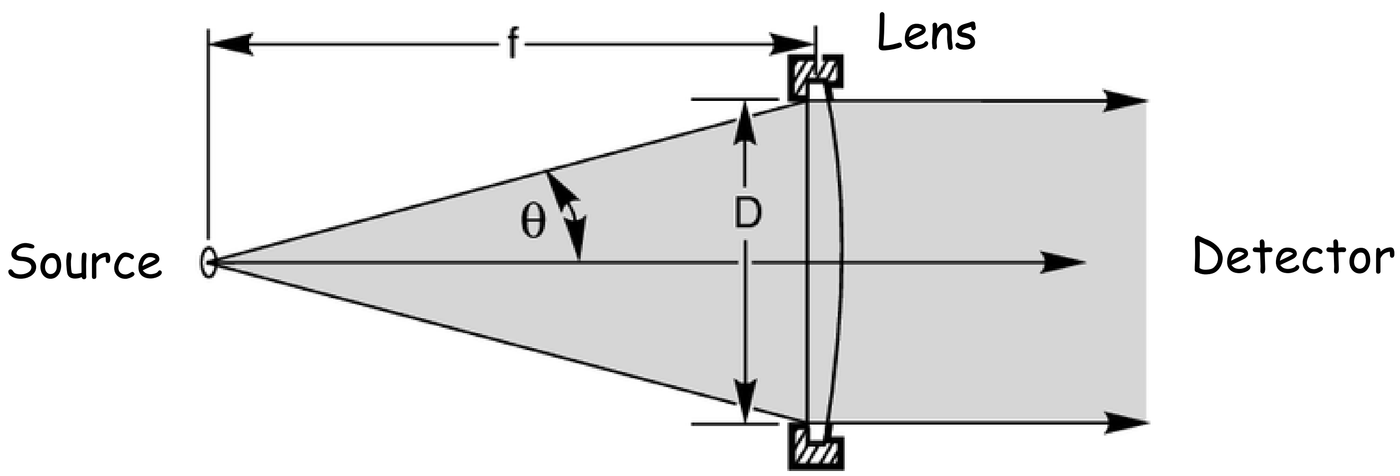


# Light Sources

## Collection and collimation

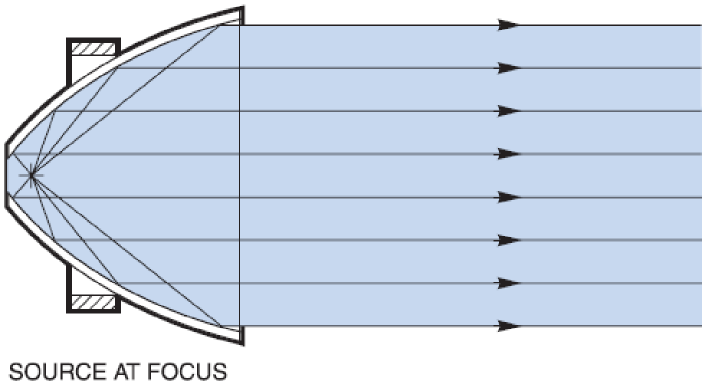
Lens: collecting and collimating light from a source

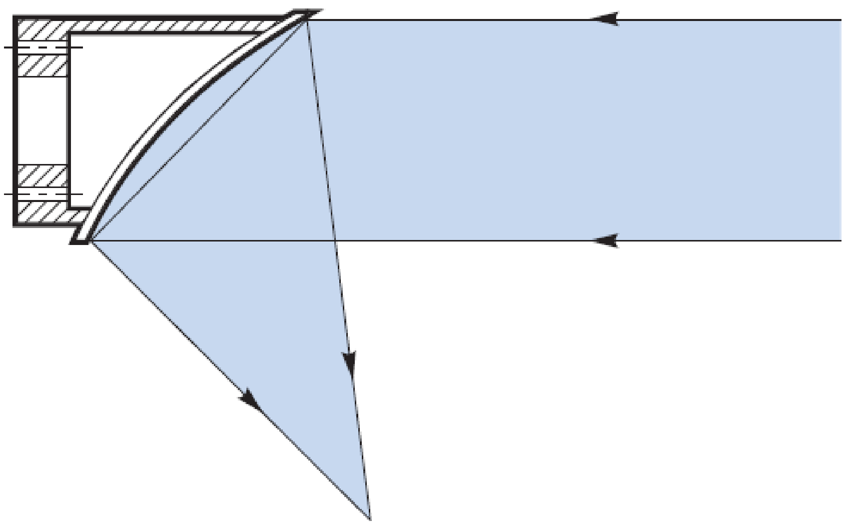



$$F\# \approx \frac{f}{D} \qquad N.A. \approx \sin\theta$$

# Light Sources
## Reflectors

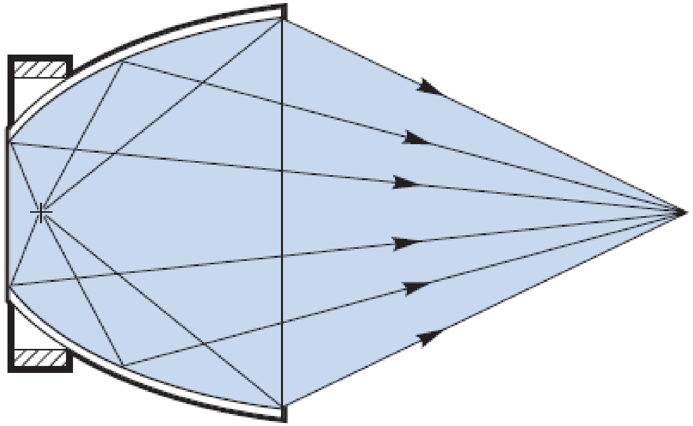
Parabolic reflectors

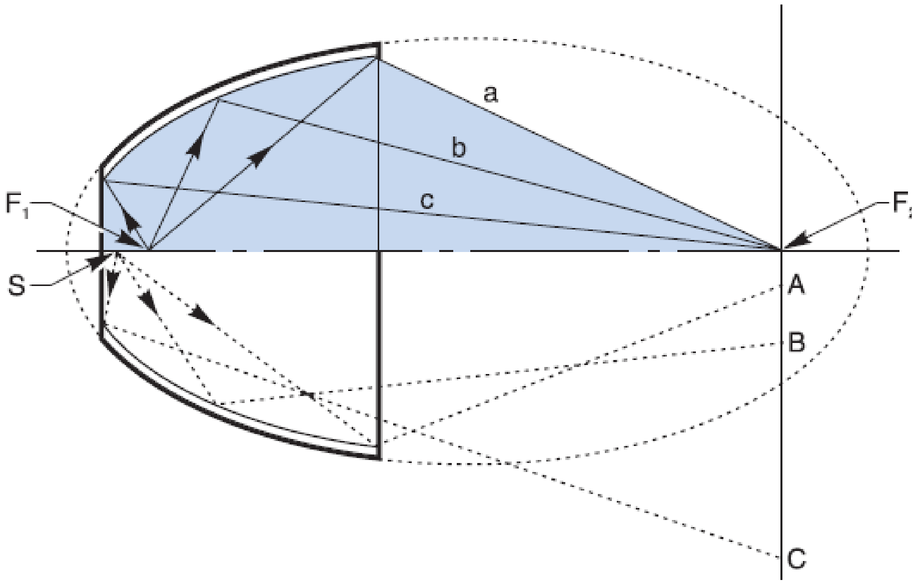


# Light Sources
## Reflectors

Ellipsoidal reflectors

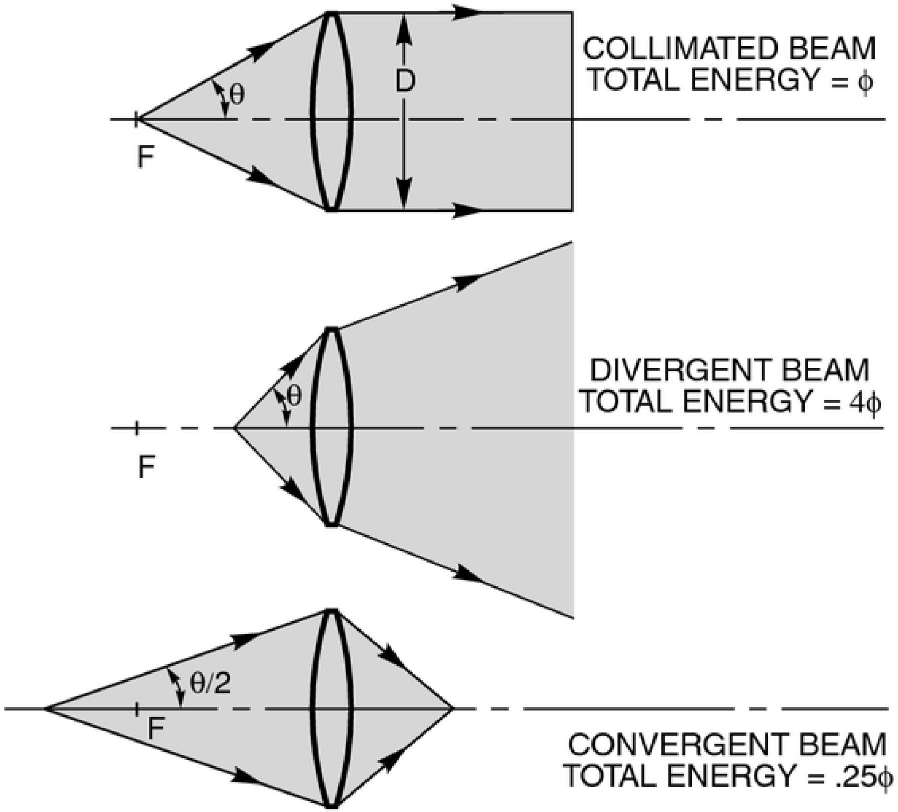




# Light Sources

## Irradiance

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



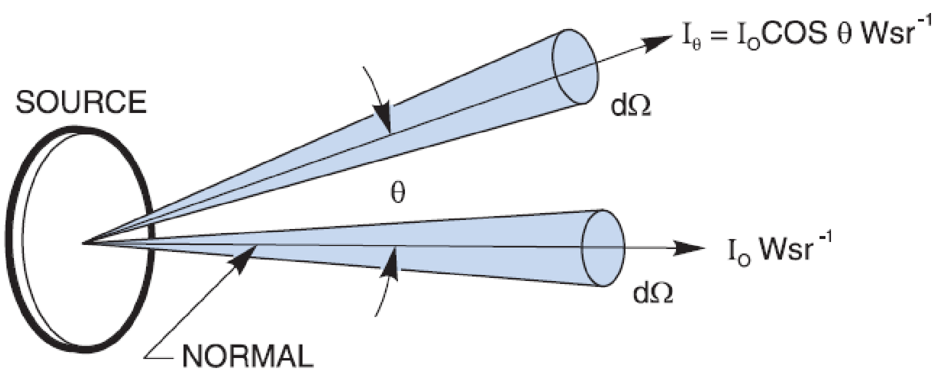
# Light Sources

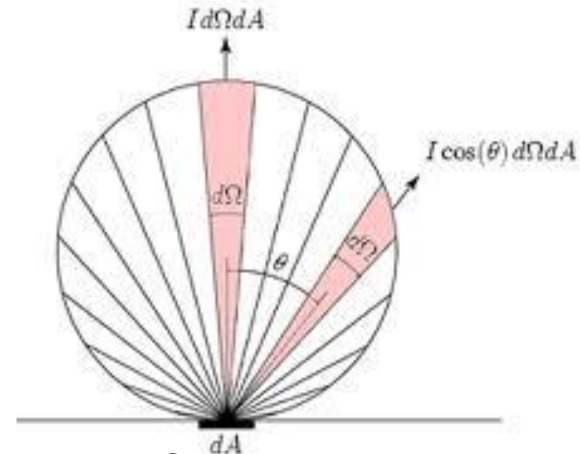
## Irradiance

### Lambert's Law

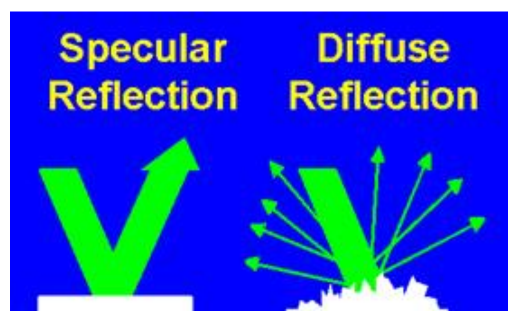
Lambert's Cosine Law holds that the radiation per unit solid angle (the radiant intensity) from a flat surface varies with the cosine of the angle to the surface normal

(Watts/steradian)




Source



# Light Sources
## Irradiance

Commonly used Radiometric, Photometric, and Photon quantities

| Radiometric | | | Photometric | | | Photon | | |
|---|---|---|---|---|---|---|---|---|
| Quantity | Usual Symbol | Units | Quantity | Usual Symbol | Units | Quantity | Usual Symbol | Units |
| Radiant Energy | $Q_e$ | J | Luminous Energy | $Q_v$ | lm s | Photon Energy | $N_p$ | * |
| Radiant Power or Flux | $\phi_e$ | W | Luminous Flux | $\phi_v$ | lm | Photon Flux | $\Phi_p = \frac{dN_p}{dt}$ | $s^{-1}$ |
| Radiant Exitance or Emittance | $M_e$ | $W\ m^{-2}$ | Luminous Exitance or Emittance | $M_v$ | $lm\ m^{-2}$ | Photon Exitance | $M_p$ | $s^{-1}\ m^{-2}$ |
| Irradiance | $E_e$ | $W\ m^{-2}$ | Illuminance | $E_v$ | lx | Photon Irradiance | $E_p$ | $s^{-1}\ m^{-2}$ |
| Radiant Intensity | $I_e$ | $W\ sr^{-1}$ | Luminous Intensity | $I_v$ | cd | Photon Intensity | $I_p$ | $s^{-1}\ sr^{-1}$ |
| Radiance | $L_e$ | $W\ sr^{-1}\ m^{-2}$ | Luminance | $L_v$ | $cd\ m^{-2}$ | Photon Radiance | $L_p$ | $s^{-1}\ sr^{-1}\ m^{-2}$ |

* **Photon quantities are expressed in number of photons followed by the units, eg. 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.

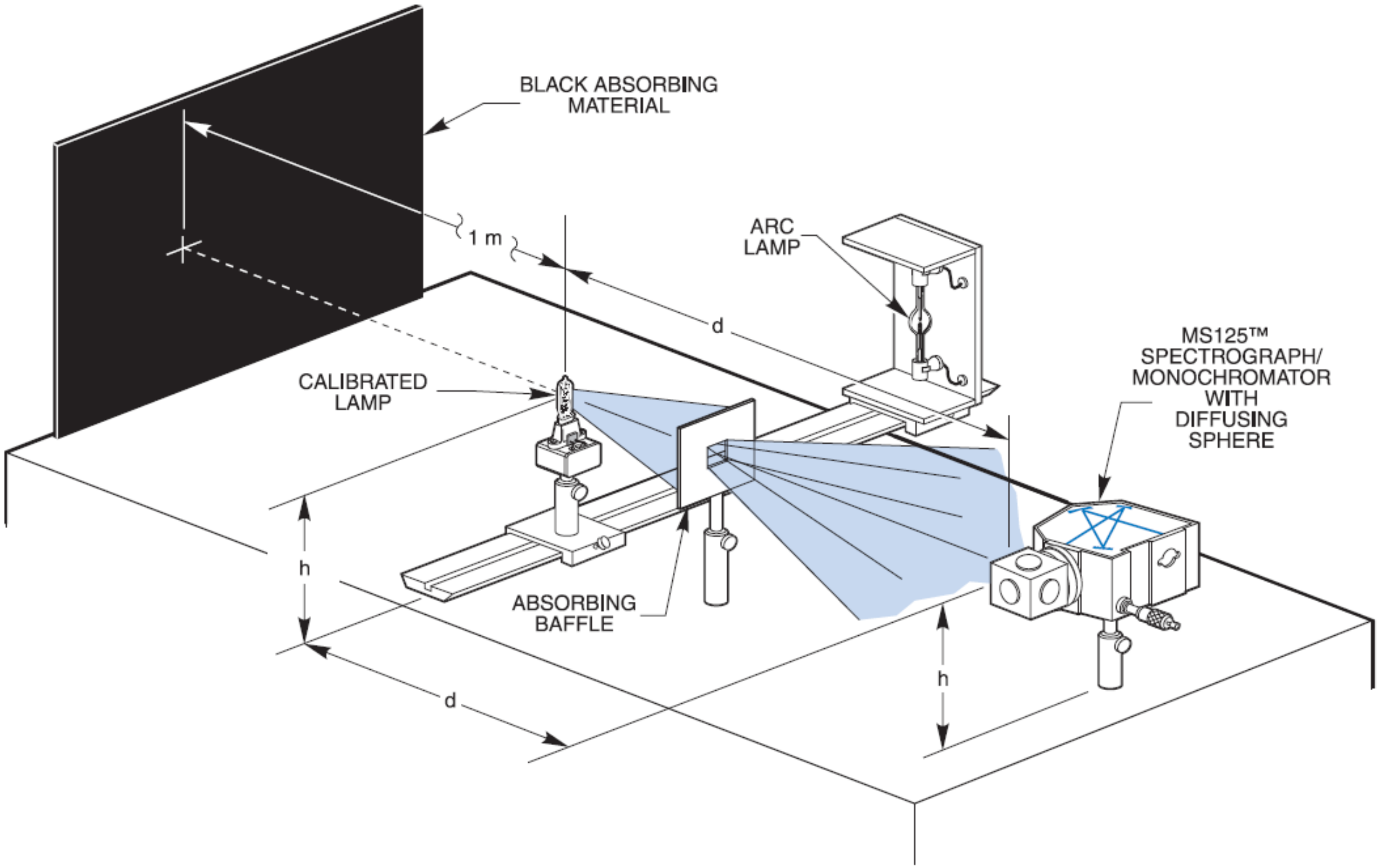
Symbols Key:

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

# Light Sources

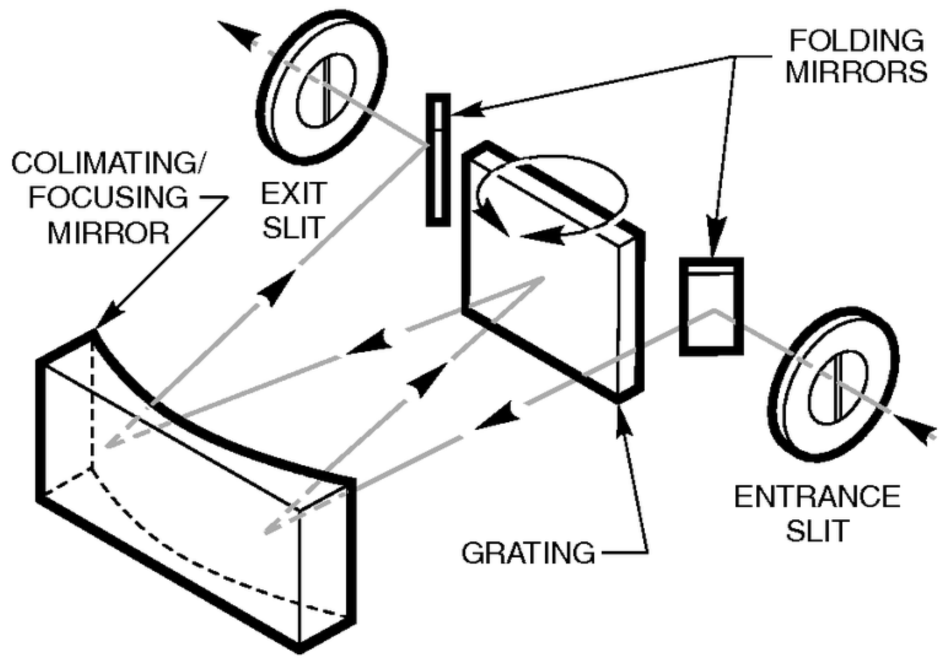
## Irradiance

### Setup for radiometric measurements

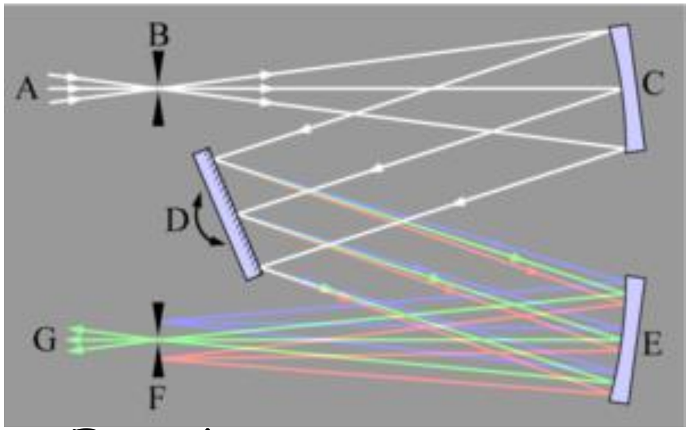


# Light Sources
## Irradiance

Typical monochromators



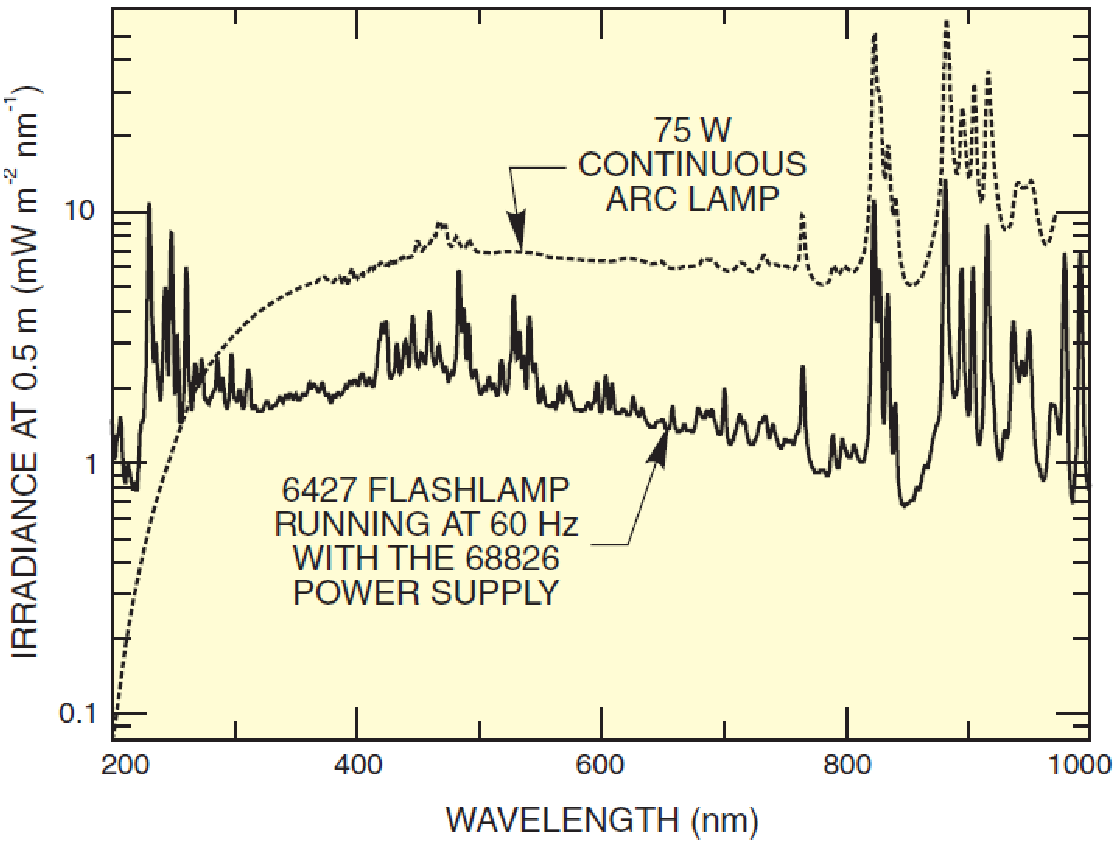

Entrance slit




Exit slit

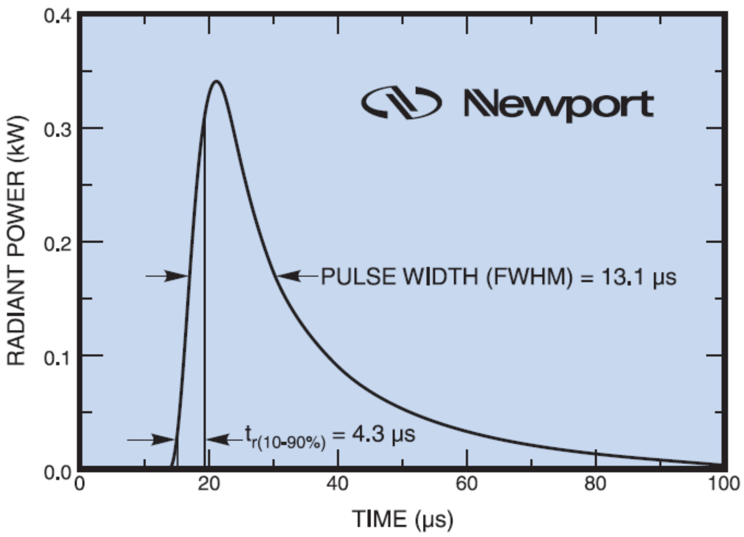
# Light Sources
## Irradiance

6426 and 6427 Xenon Flashlamps, with 68826 Power Supply.



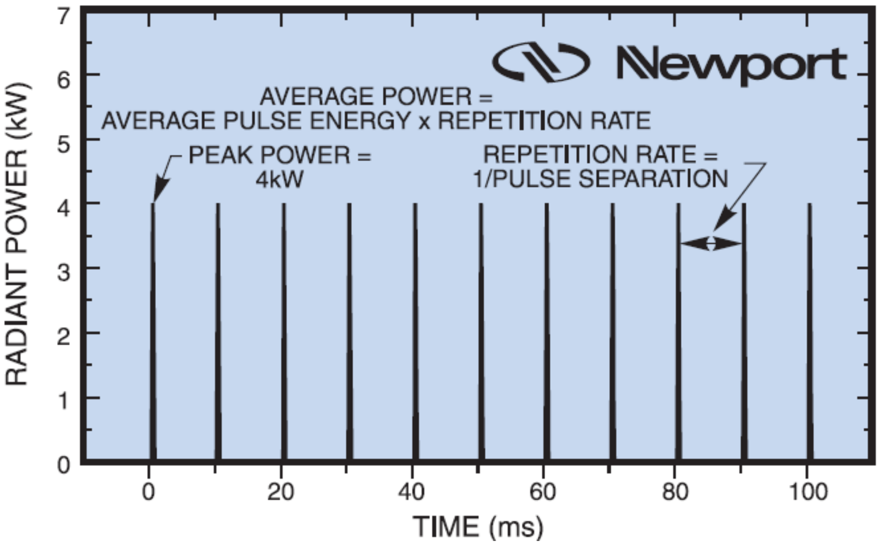
# Light Sources

## Pulsed source




Typical single pulse

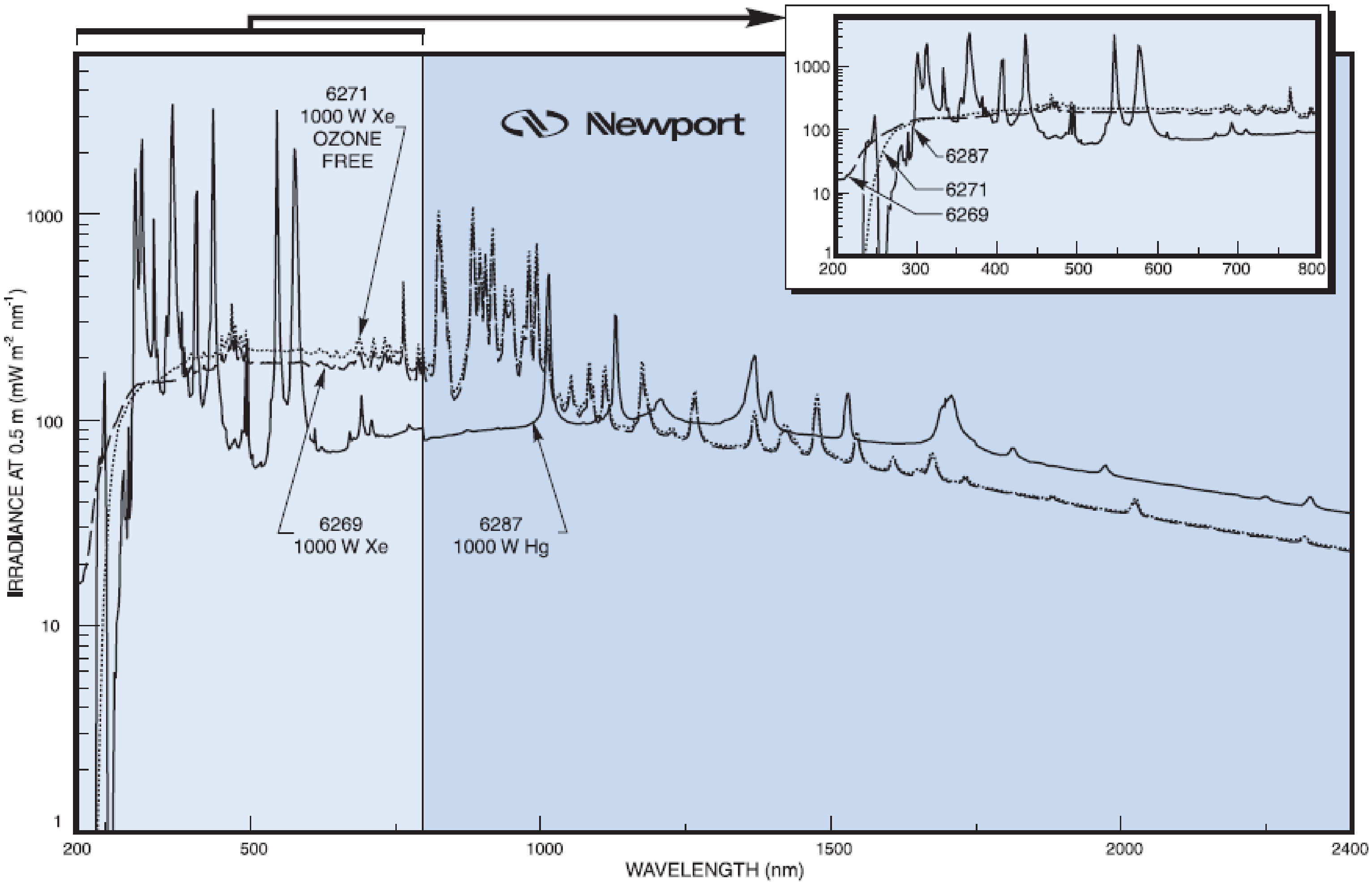
Typical pulsetrain display. The repetition rate shown is 100 Hz, the peak power 4 kW.



# Light Sources

## Arc Lamps

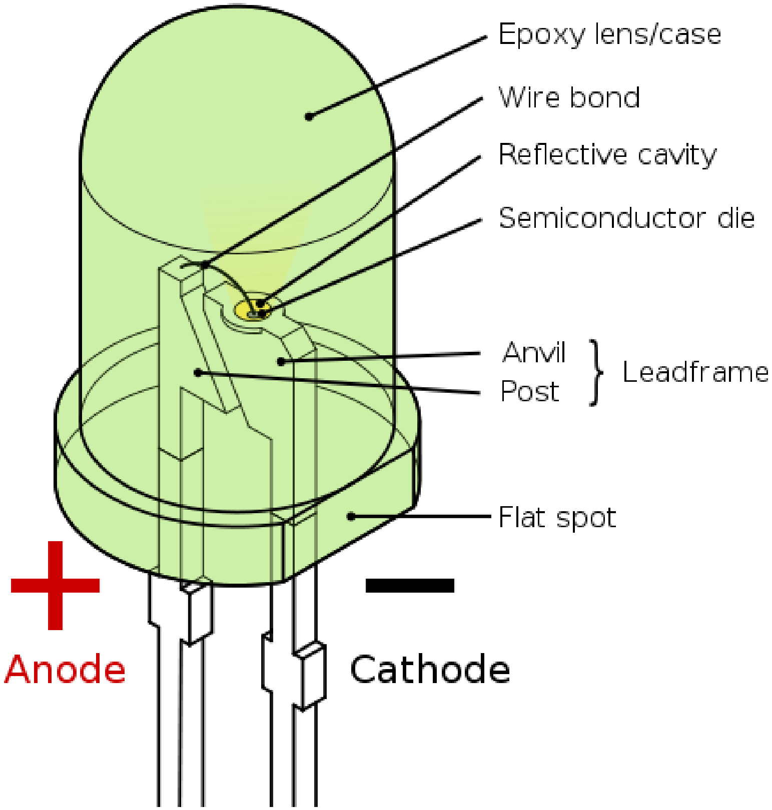
Spectral irradiance of various Arc Lamps



# 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

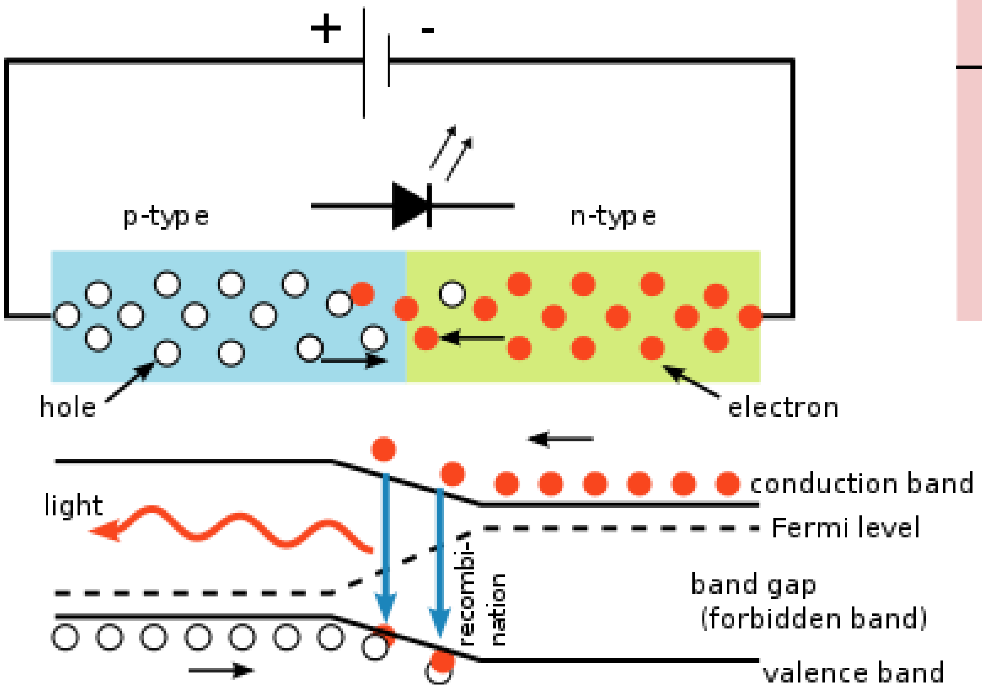


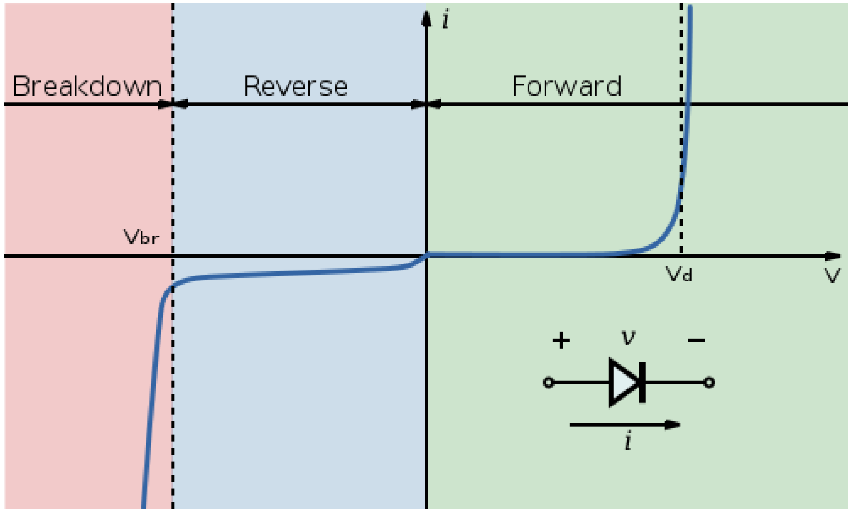

An LED consists of a chip of semiconducting material doped with impurities to create a p-n junction

# 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

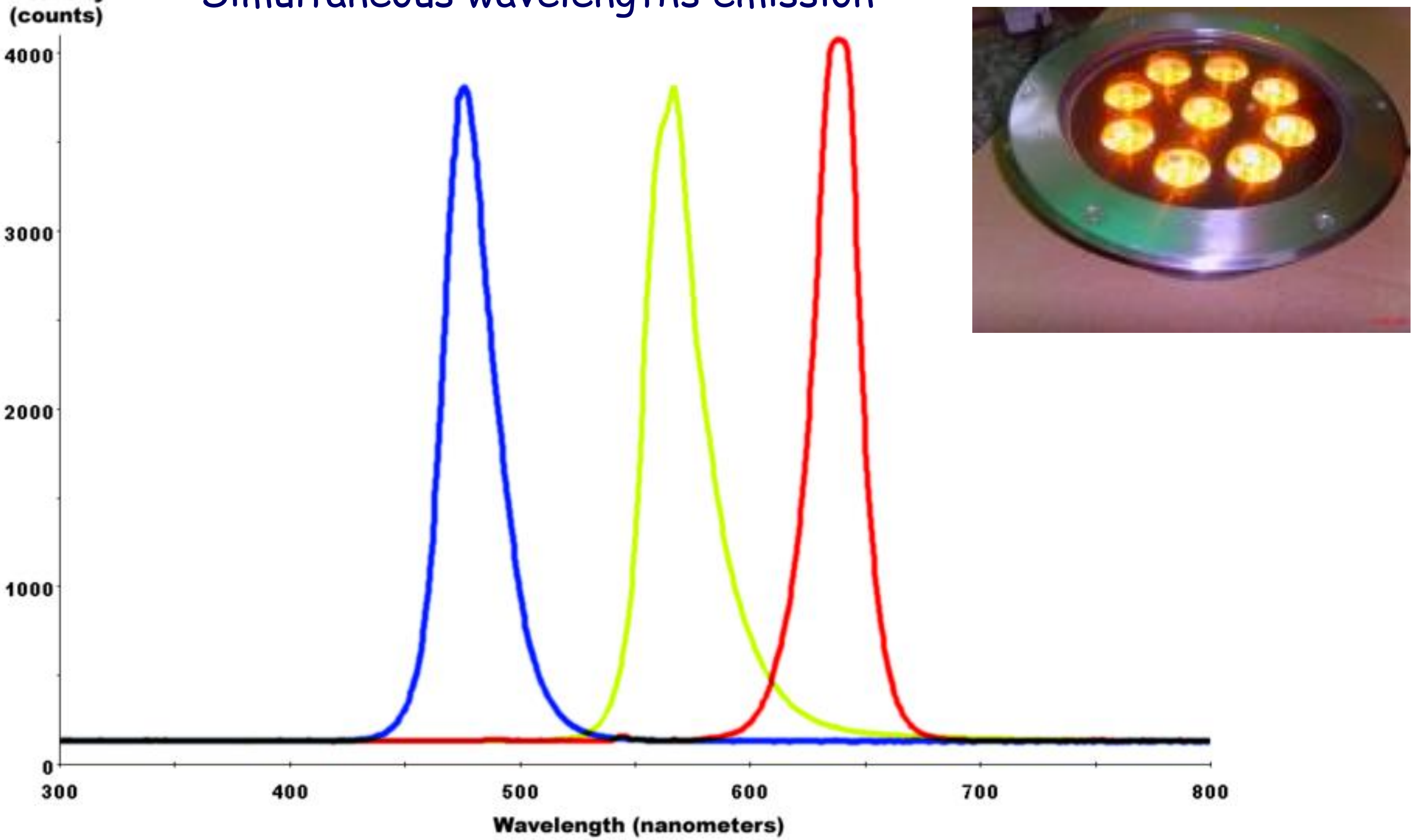
## Light emitting diode (LED)

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

# Light Sources

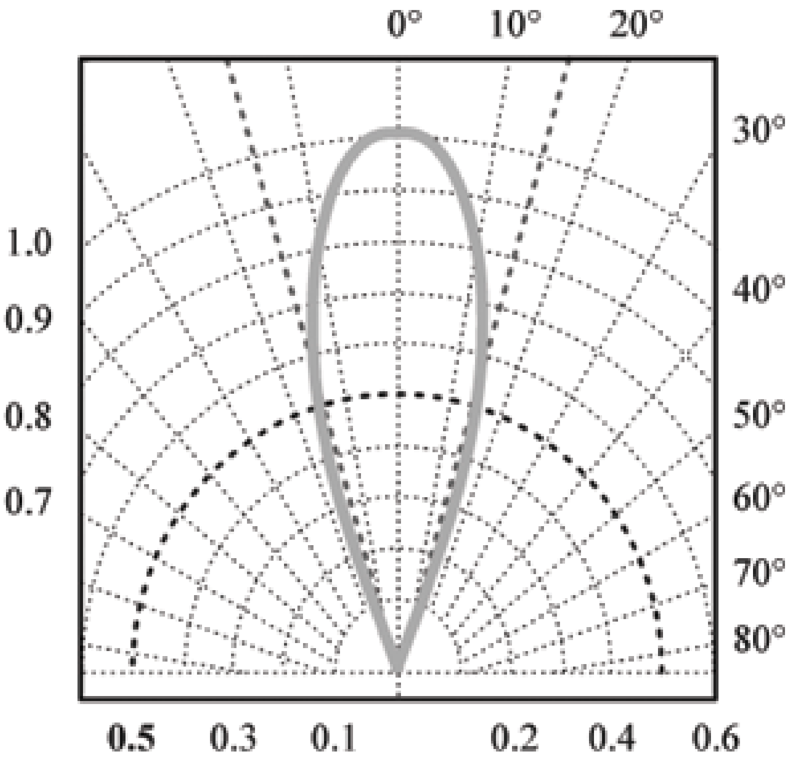
## Light emitting diode (LED)

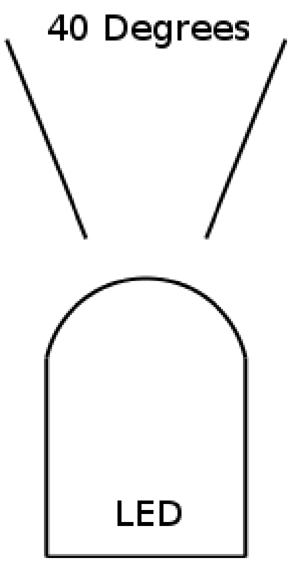
Simultaneous wavelengths emission



# Light Sources
## Light emitting diode (LED)

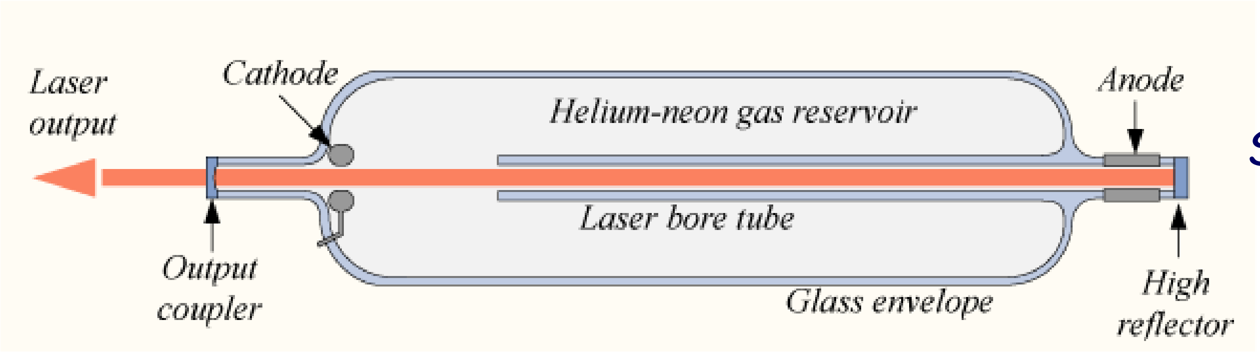
Typical emission flux



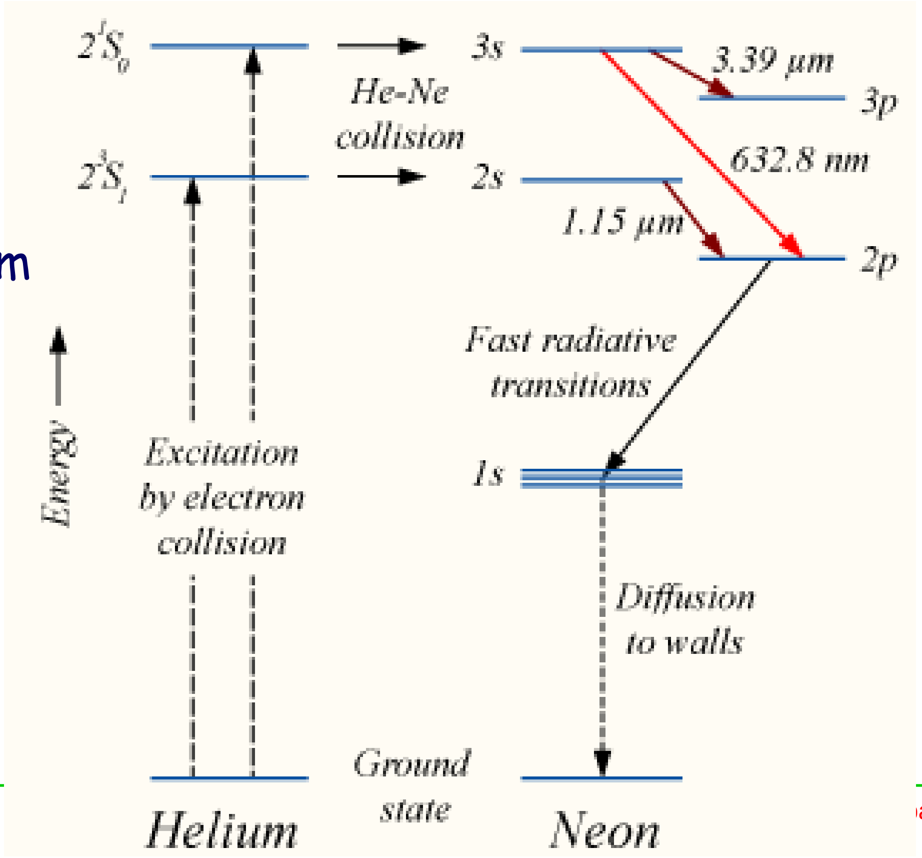




# Light Sources

## Gas lasers: He-Ne




Schematic diagram of a He-Ne laser

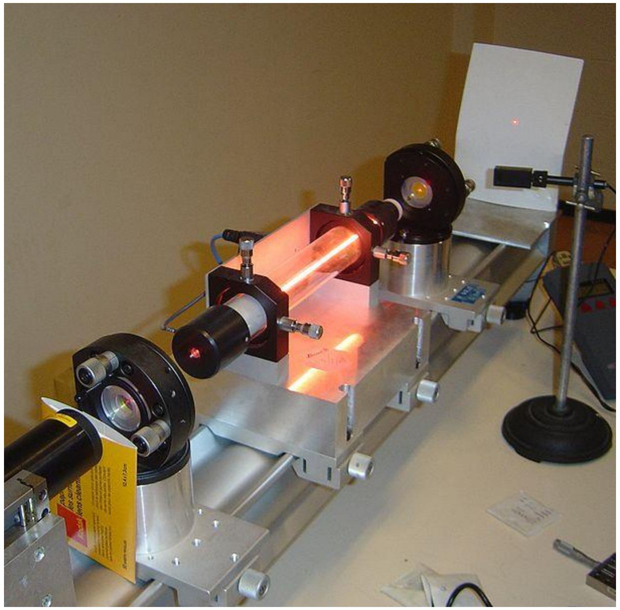


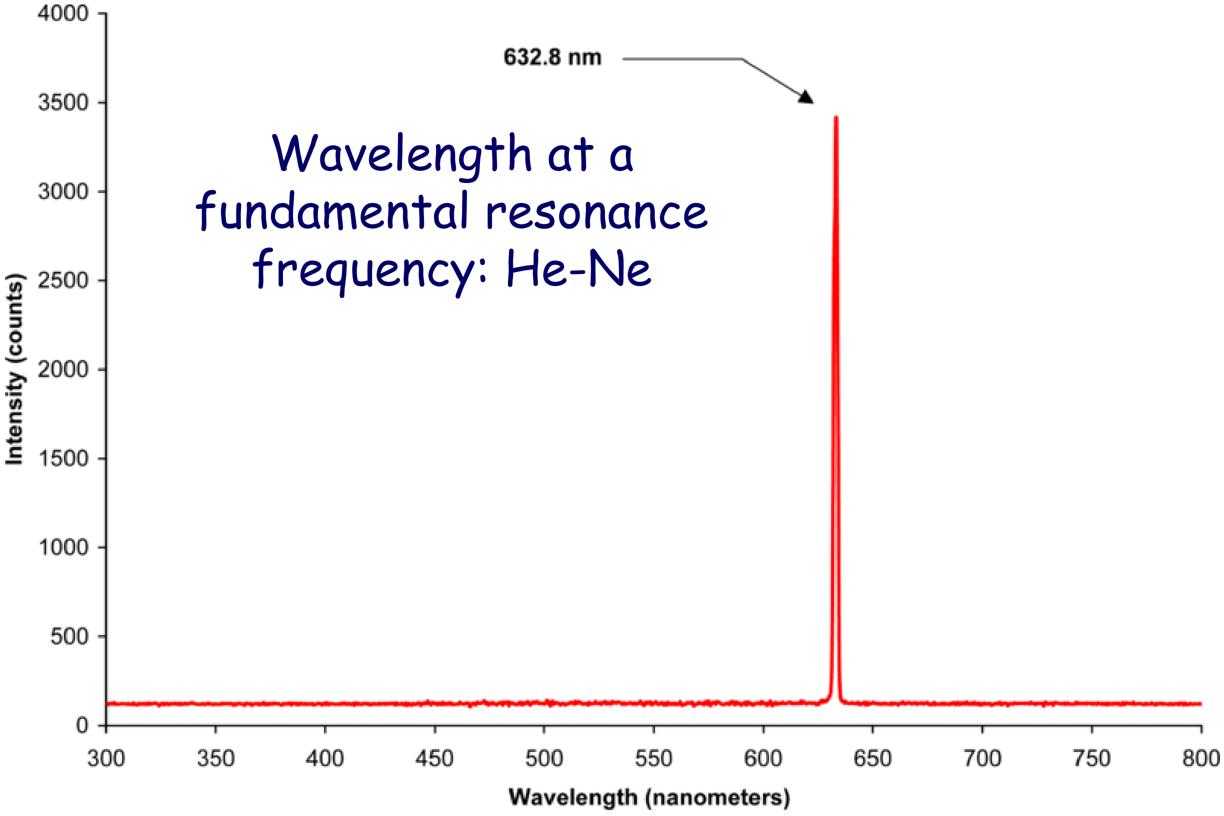

Energy level diagram of a He-Ne laser

# Light Sources

## Gas lasers: He-Ne

He-Ne laser



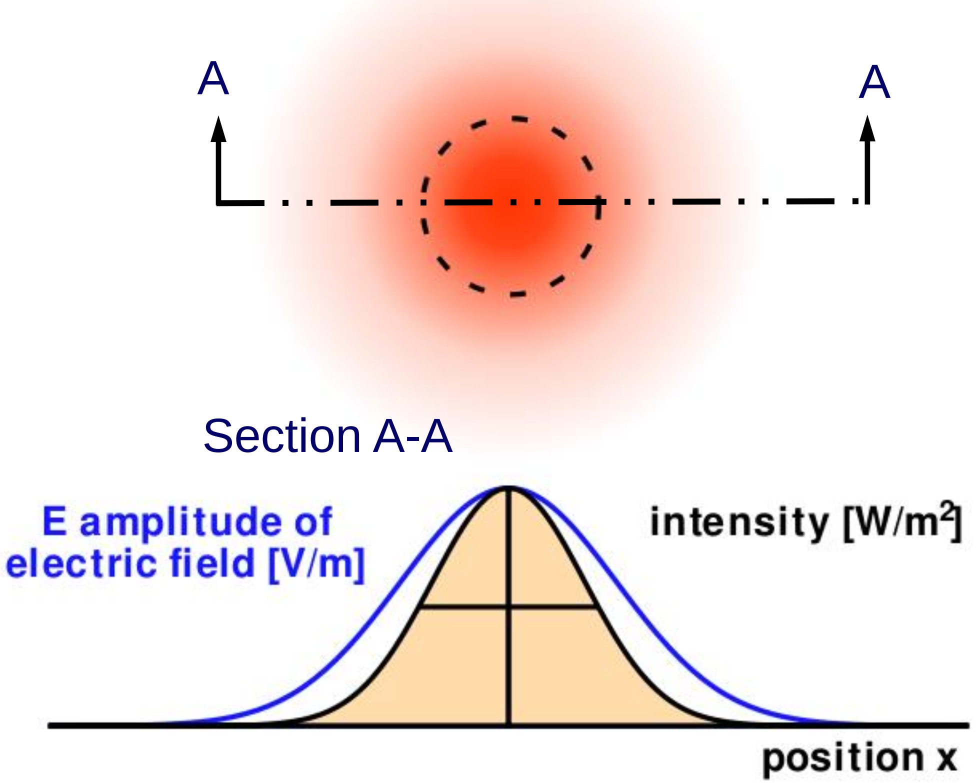



Wavelength at a fundamental resonance frequency: He-Ne

# Light Sources
## Transversal profile

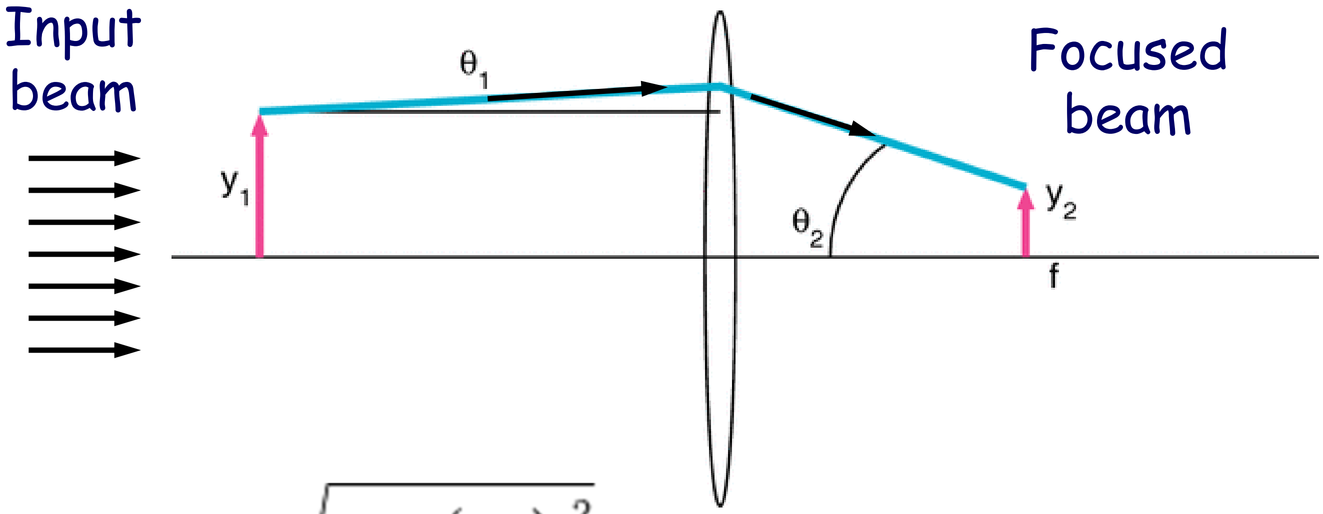
He-Ne cross section of intensity

Gaussian intensity distribution

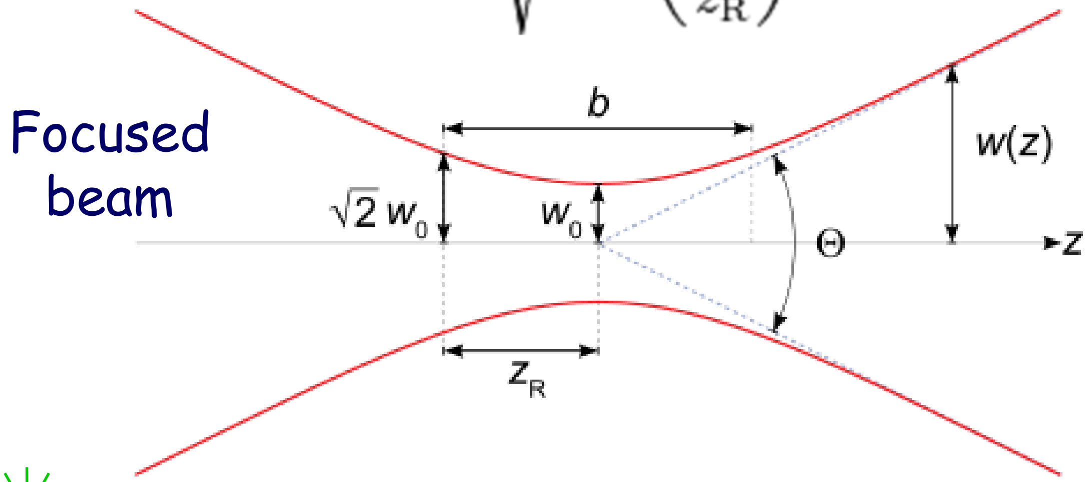


# Light Sources

## Beam diameter: focused beam




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

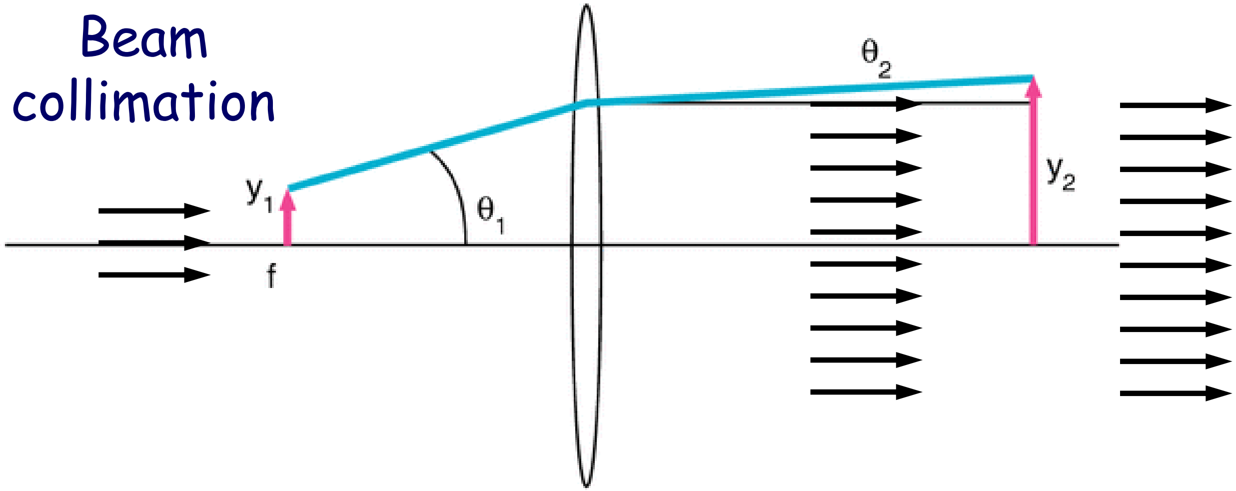



**Gaussian beam width** $w(z)$ as a function of the axial distance $z$. $w_0$: beam waist; $b$: depth of focus; $z_R$: Rayleigh range; $\Theta$: total angular spread

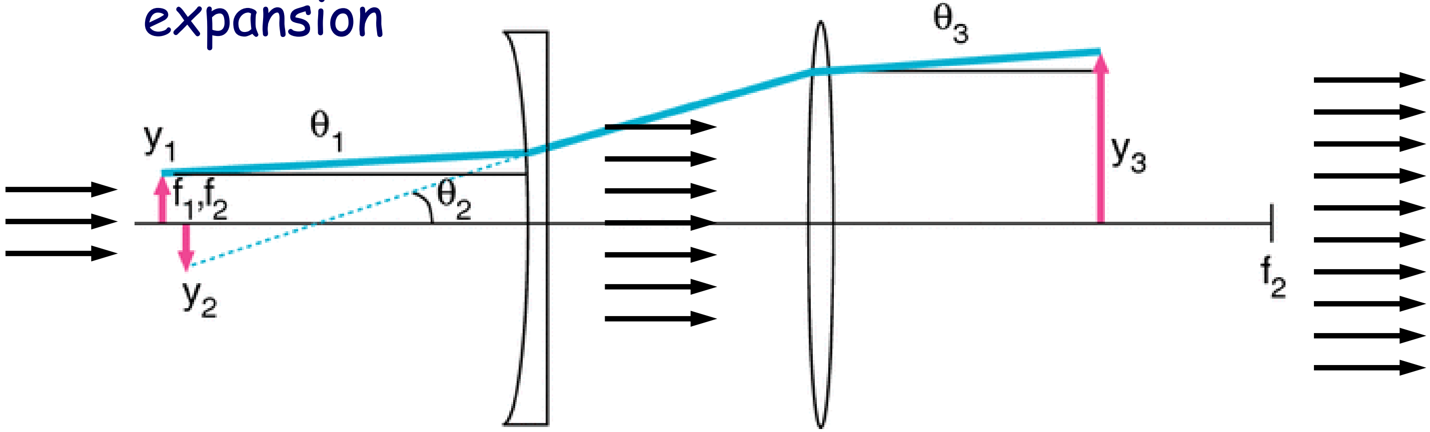
# Light Sources

## Collimation and expansion of a laser beam

Beam collimation




Beam expansion



# Light Sources

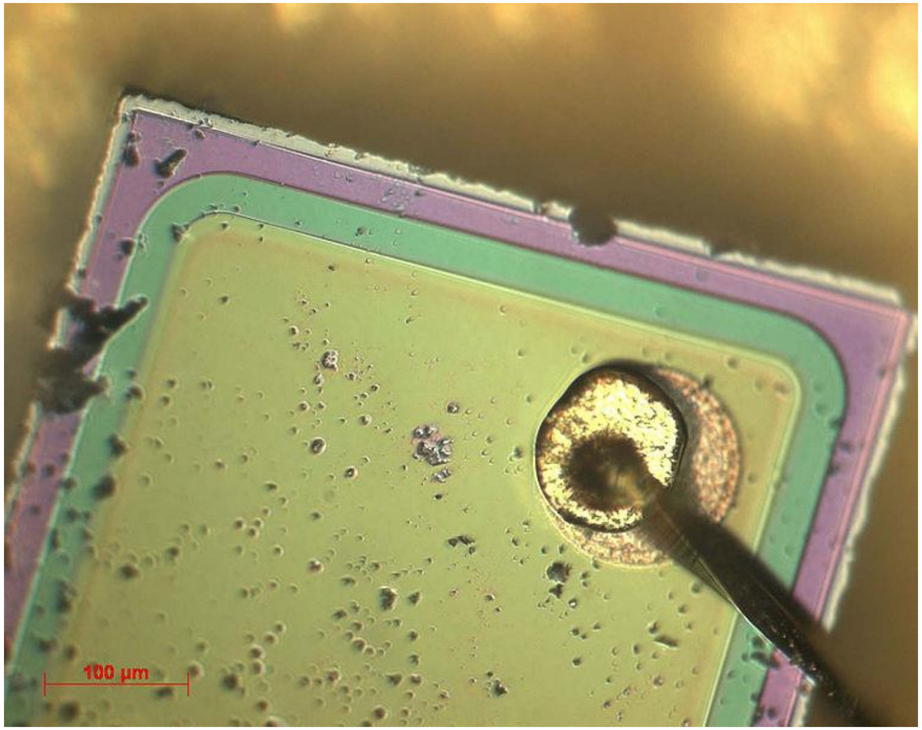
## Lasers: gas

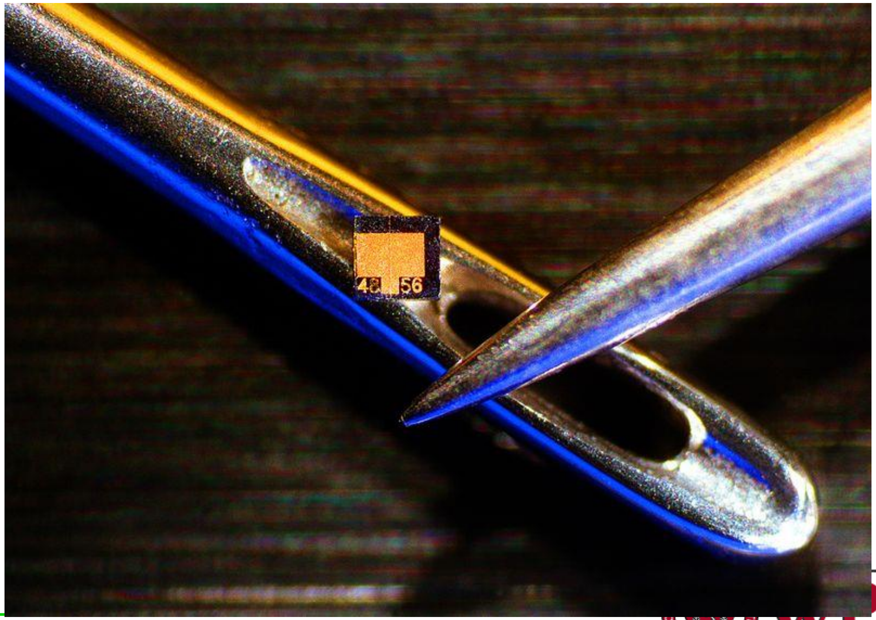
| Laser gain medium and type | Operation wavelength(s) | Pump source | Applications and notes |
|---|---|---|---|
| Helium-neon laser | 632.8 nm (543.5 nm, 593.9 nm, 611.8 nm, 1.1523 μm, 1.52 μm, 3.3913 μm) | Electrical discharge | Interferometry, holography, spectroscopy, barcode scanning, alignment, optical demonstrations. |
| Argon laser | 454.6 nm, 488.0 nm, 514.5 nm (351 nm, 363.8, 457.9 nm, 465.8 nm, 476.5 nm, 472.7 nm, 528.7 nm, also frequency doubled to provide 244 nm, 257 nm) | Electrical discharge | Retinal phototherapy (for diabetes), lithography, confocal microscopy, spectroscopy pumping other lasers. |
| Krypton laser | 416 nm, 530.9 nm, 568.2 nm, 647.1 nm, 676.4 nm, 752.5 nm, 799.3 nm | Electrical discharge | Scientific research, mixed with argon to create "white-light" lasers, light shows. |
| Xenon ion laser | Many lines throughout visible spectrum extending into the UV and IR. | Electrical discharge | Scientific research. |
| Nitrogen laser | 337.1 nm | Electrical discharge | Pumping of dye lasers, measuring air pollution, scientific research. Nitrogen lasers can operate superradiantly (without a resonator cavity). Amateur laser construction. See TEA laser |
| Carbon dioxide laser | 10.6 μm, (9.4 μm) | Transverse (high power) or longitudinal (low power) electrical discharge | Material processing (cutting, welding, etc.), surgery. |
| Carbon monoxide laser | 2.6 to 4 μm, 4.8 to 8.3 μm | Electrical discharge | Material processing (engraving, welding, etc.), photoacoustic spectroscopy. |
| Excimer laser | 193 nm (ArF), 248 nm (KrF), 308 nm (XeCl), 353 nm (XeF) | Excimer recombination via electrical discharge | Ultraviolet lithography for semiconductor manufacturing, laser surgery, LASIK. |

# Light Sources

## Laser diodes: semiconductors

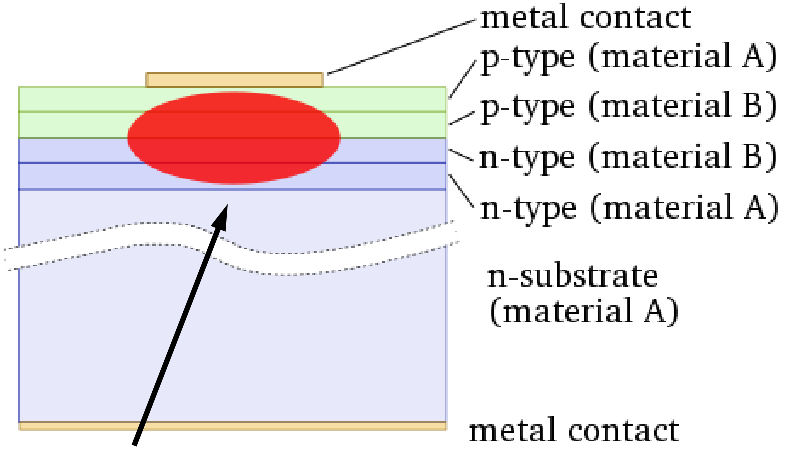
Laser diodes: package and semiconductor dyes



# Light Sources
## Laser diodes: semiconductors

Diagram of front view of a double heterostructure laser diode




Elliptical output profile of intensity

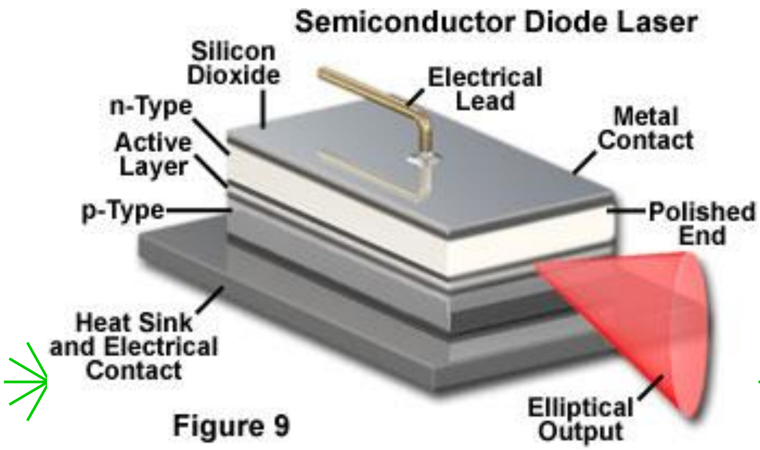
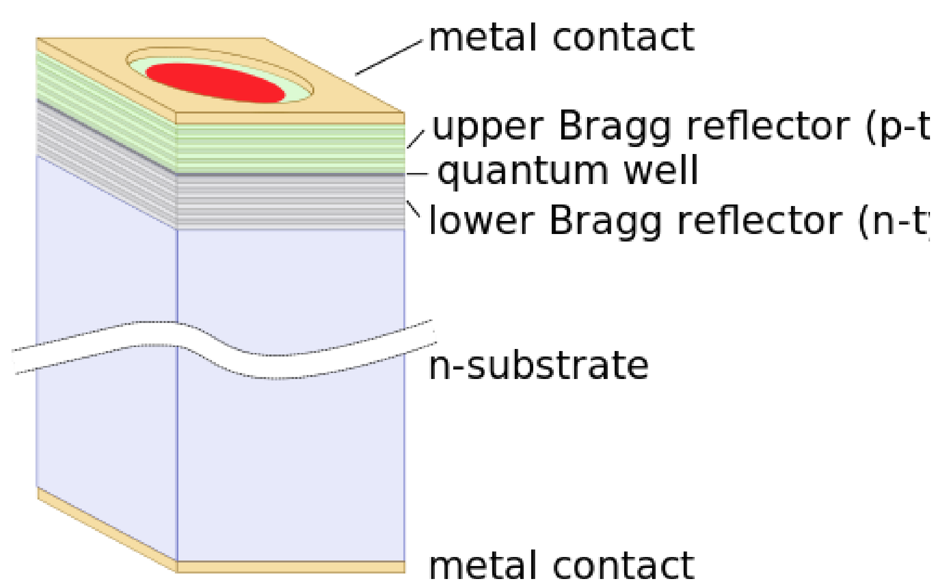


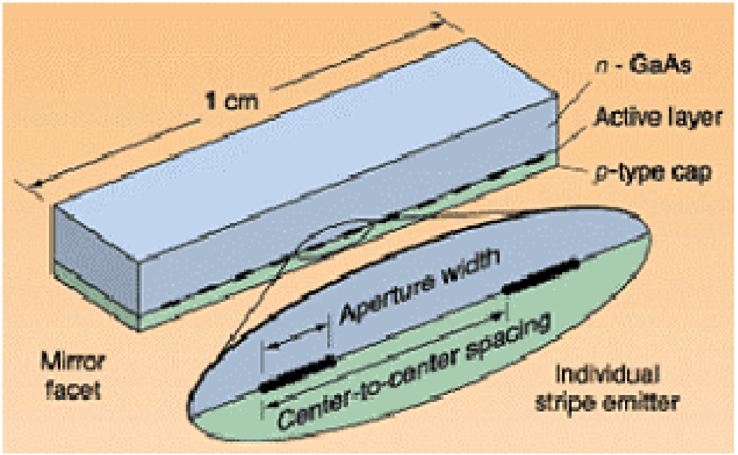

Diagram of a simple vertical-cavity surface emitting laser (VCSEL) structure



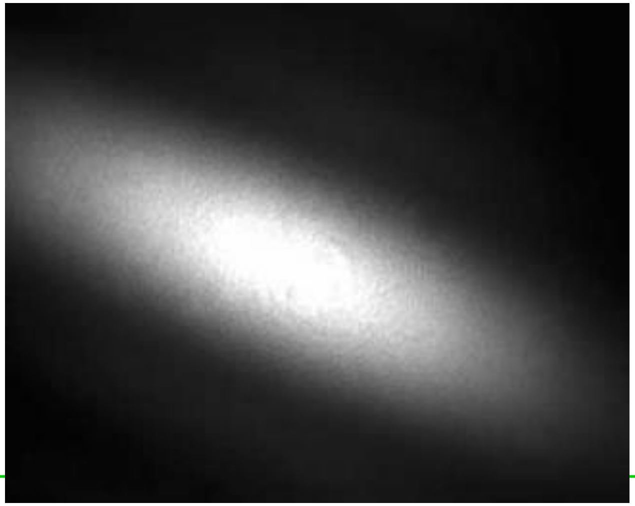
# Light Sources

## Laser diodes: semiconductors

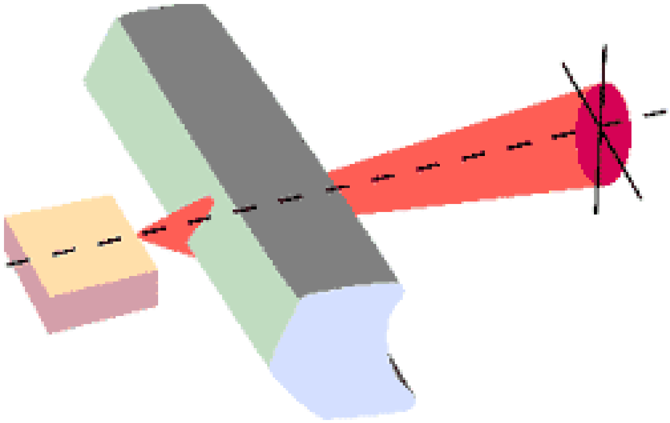
### Elliptical output profile of intensity



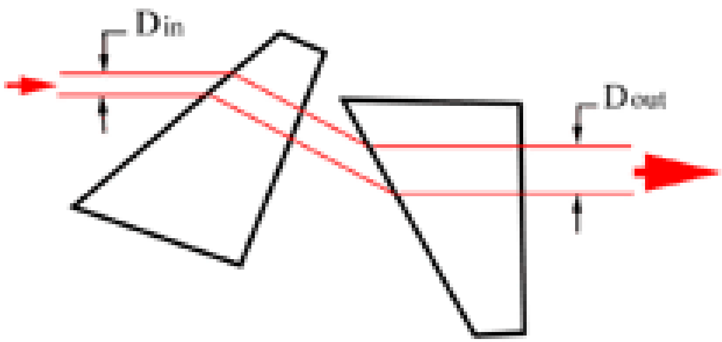

The laser bar structure of the laser-diode array (LDA)



### Cylindrical microlens for laser diode beam correction



### Anamorphic prisms for laser diode beam correction



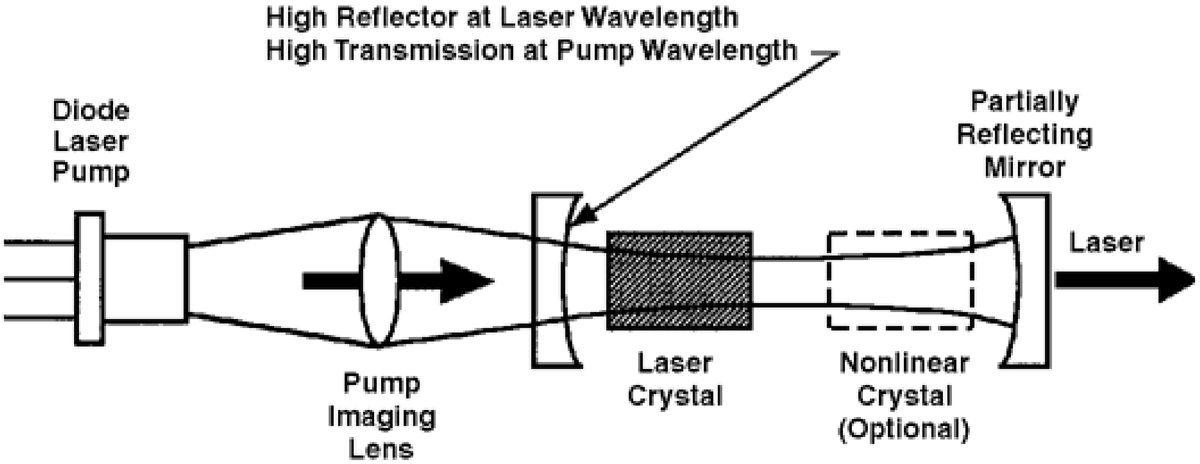
# Light Sources

## Laser diodes: semiconductors

| Laser gain medium and type | Operation wavelength(s) | Pump source | Applications and notes |
|---|---|---|---|
| Semiconductor laser diode (general information) | 0.4-20 µm, depending on active region material. | Electrical current | Telecommunications, holography, printing, weapons, machining, welding, pump sources for other lasers. |
| GaN | 0.4 µm | | Optical discs. 405 nm is used in Blu-Ray discs reading/recording. |
| AlGaInP, AlGaAs | 0.63-0.9 µm | | 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. |
| InGaAsP | 1.0-2.1 µm | | Telecommunications, solid-state laser pumping, machining, medical.. |
| lead salt | 3-20 µm | | |
| Vertical cavity surface emitting laser (VCSEL) | 850 - 1500 nm, depending on material | | Telecommunications |
| Quantum cascade laser | Mid-infrared to far-infrared. | | Research,Future applications may include collision-avoidance radar, industrial-process control and medical diagnostics such as breath analyzers. |
| Hybrid silicon laser | Mid-infrared | | Research |

# Light Sources

## Solid state lasers

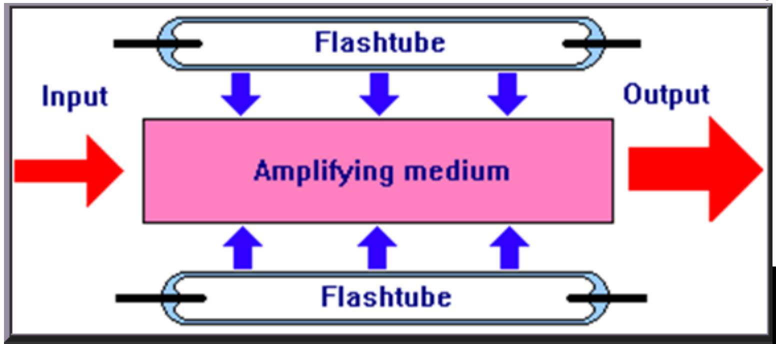


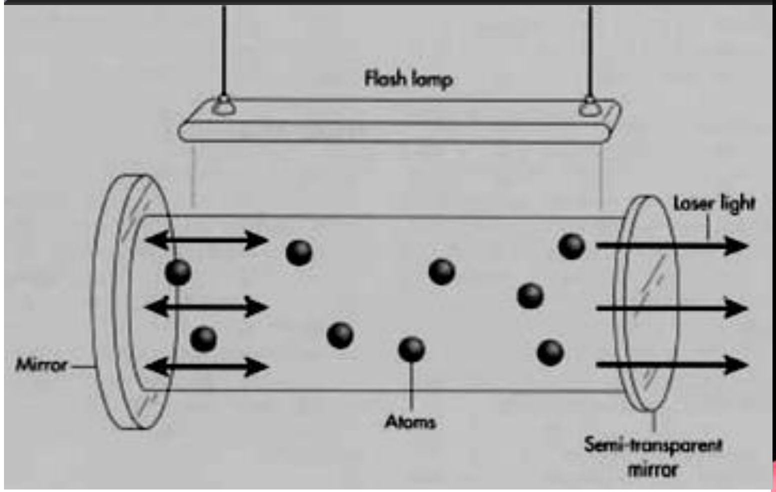

Nd:YAG laser used as an optical pump


Neodymium-doped glass rod

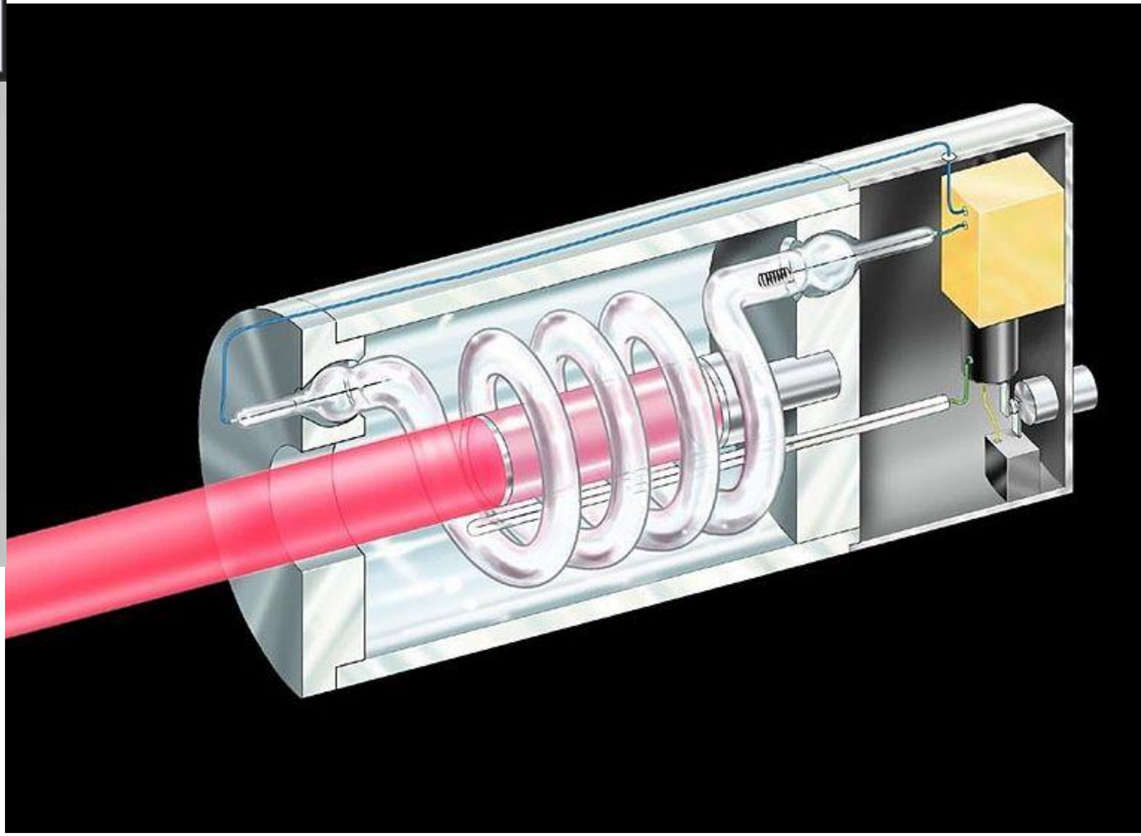
# Light Sources

## Solid state lasers: Ruby laser – first visible laser invented




Synthetic ruby crystal used as gain medium



*Theodore Maiman, 1960*

# Light Sources

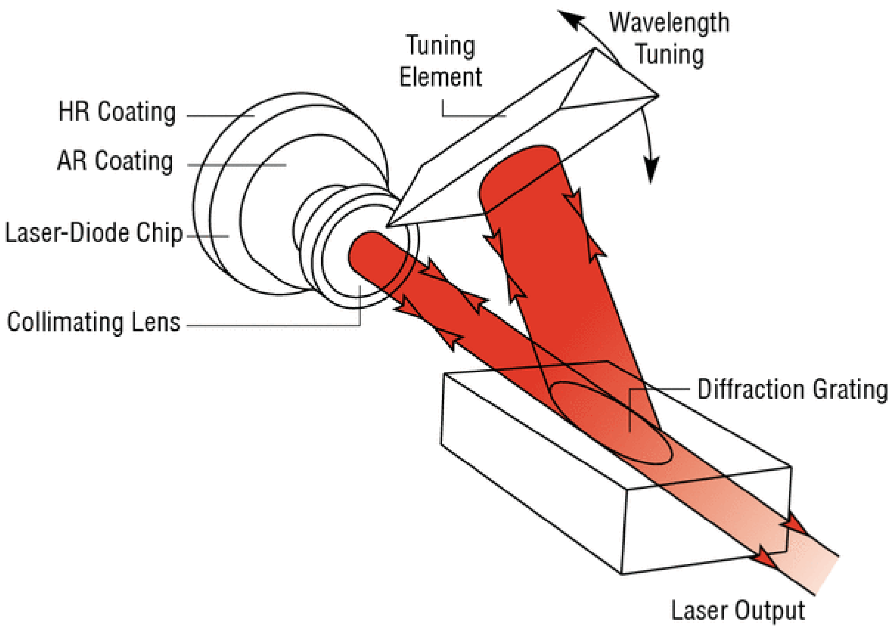
## Solid state lasers

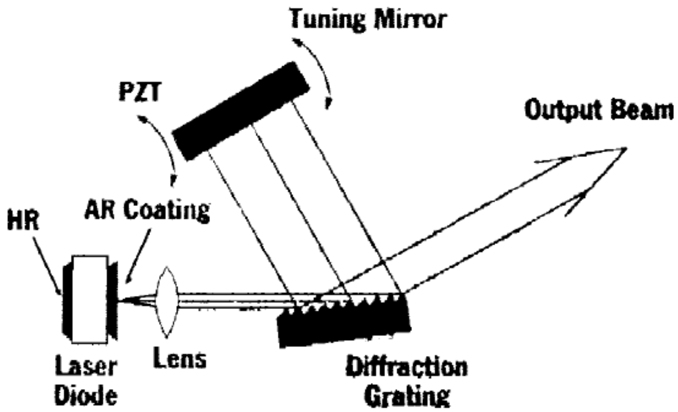
| Laser gain medium and type | Operation wavelength(s) | Pump source | Applications and notes |
|---|---|---|---|
| Ruby laser | 694.3 nm | Flashlamp | Holography, tattoo removal. The first type of visible light laser invented; May 1960. |
| Nd:YAG laser | 1.064 µm, (1.32 µm) | Flashlamp, laser diode | 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) |
| Er:YAG laser | 2.94 µm | Flashlamp, laser diode | Periodontal scaling, Dentistry |
| Neodymium YLF (Nd:YLF) solid-state laser | 1.047 and 1.053 µm | Flashlamp, laser diode | Mostly used for pulsed pumping of certain types of pulsed Ti:sapphire lasers, combined with frequency doubling. |
| Neodymium doped Yttrium orthovanadate (Nd:$YVO_4$) laser | 1.064 µm | laser diode | 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:$YVO_4$ laser is also the normal way of making a green laser pointer. |
| Neodymium doped yttrium calcium oxoborate Nd:$YCa_4O(BO_3)_3$ or simply Nd:YCOB | ~1.060 µm (~530 nm at second harmonic) | laser diode | Nd:YCOB is a so called "self-frequency doubling" 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. |
| Neodymium glass (Nd:Glass) laser | ~1.062 µm (Silicate glasses), ~1.054 µm (Phosphate | Flashlamp, laser diode | 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 |

# Light Sources

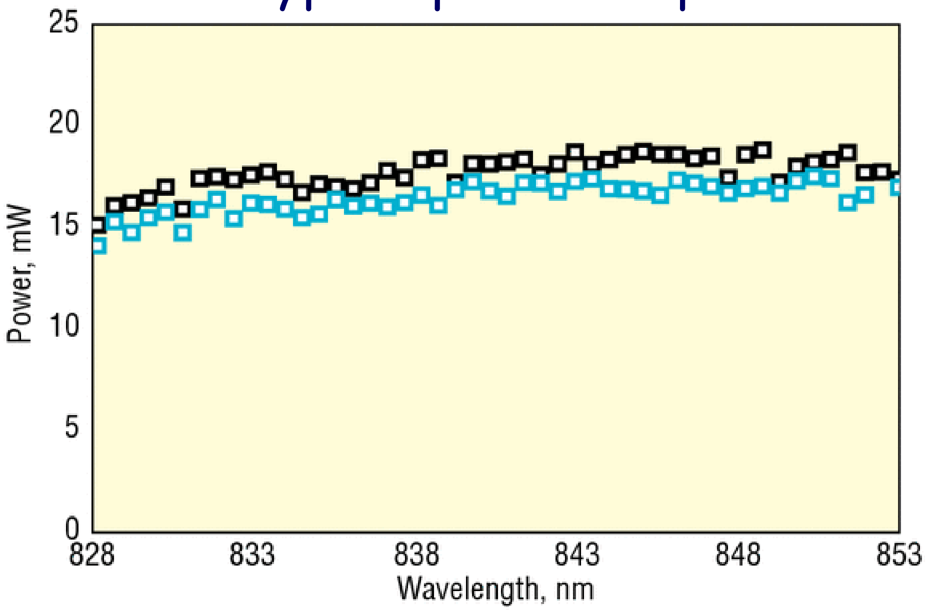
## Semiconductor, tunable lasers

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