



Empa

Materials Science and Technology

EPFL

Laser Processing of Materials

Laser as Light Source

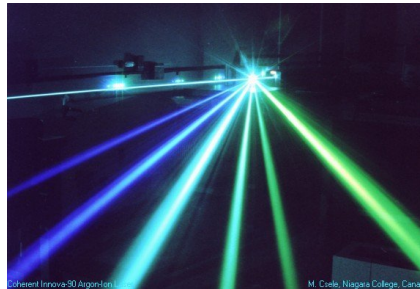
Patrik Hoffmann

Content

- Laser Principles
- Properties of Laser Light
- Laser Types
- Pulsed Lasers
- Light Emitting Diodes (LEDs)

LASER

- **L**ight
 - **A**mplification by
 - **S**timulated
 - **E**mission
 - **R**adiation
- **L**egal
 - **A**musement of
 - **S**tudents
 - **E**ngineers and
 - **R**esearchers



Basics of lasers in case of interest:

Principles of Lasers. by **Orazio Svelto** (Springer, 5ed. 2010).

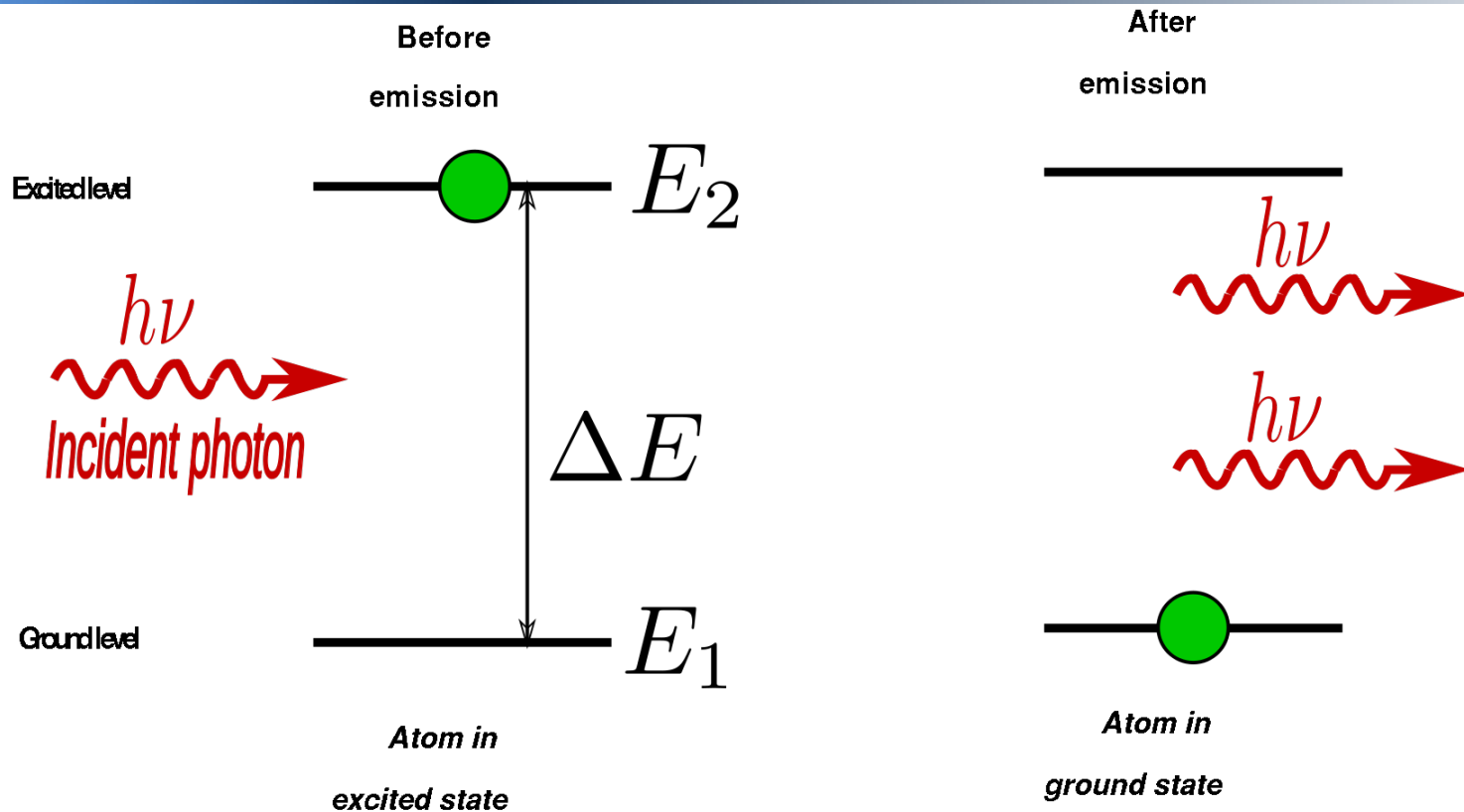
Lasers. by **Anthony E. Siegman.** (Univ Science Books, 1986)

Key Concepts/Elements

What is ...?

- Stimulated emission
- Population inversion
- Light amplification
- Pumping process

Stimulated Emission

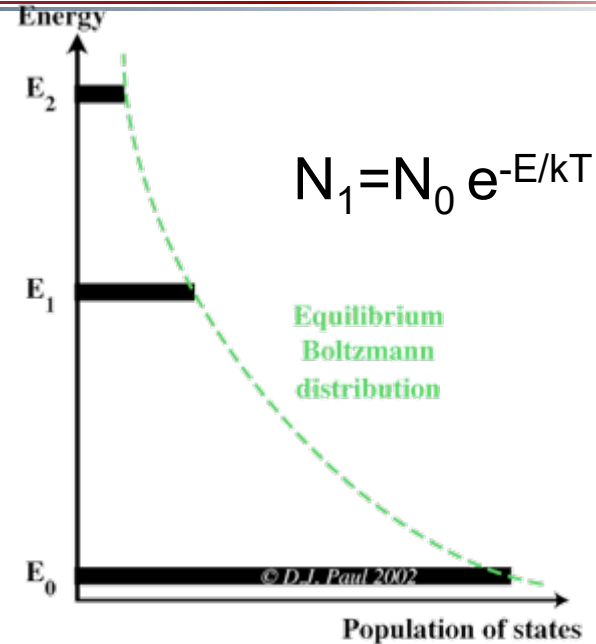


Frequency, Phase, Direction of stimulated emission photon are identical to that of the incident photon

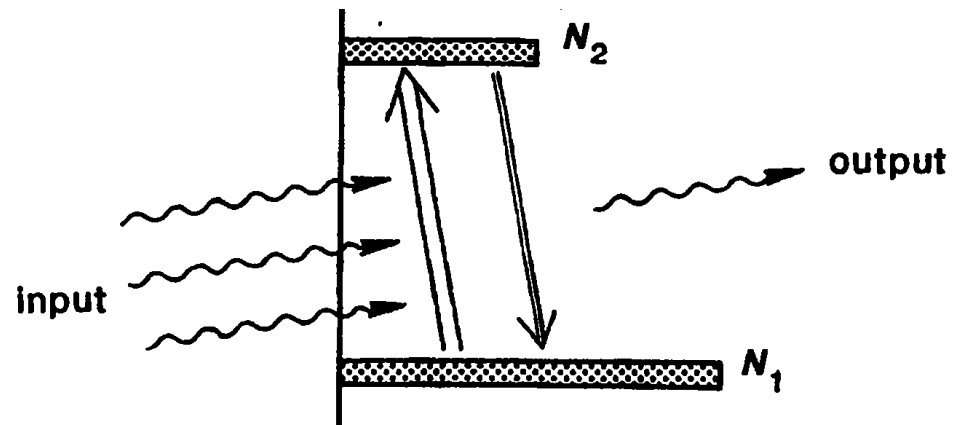
⇒ reason for the special properties of the laser light

Energy Levels Population Inversion

normally energy levels are populated according to Boltzmann distribution

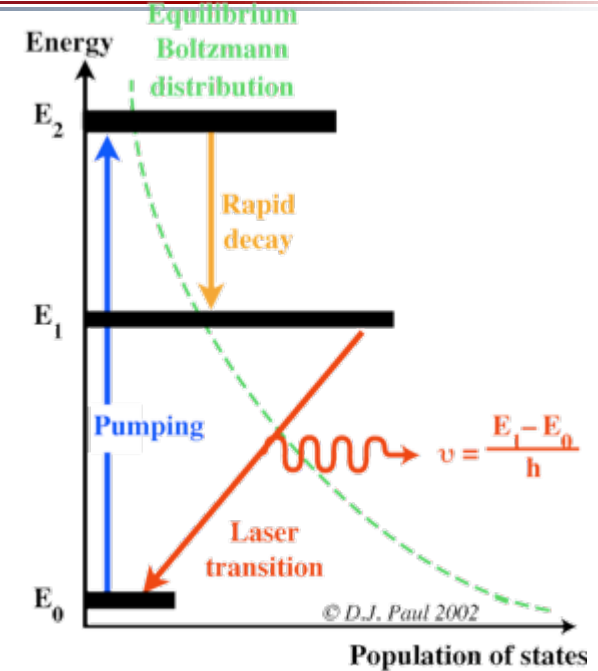


which results in absorption of light prevail over the stimulated emission at transition frequency



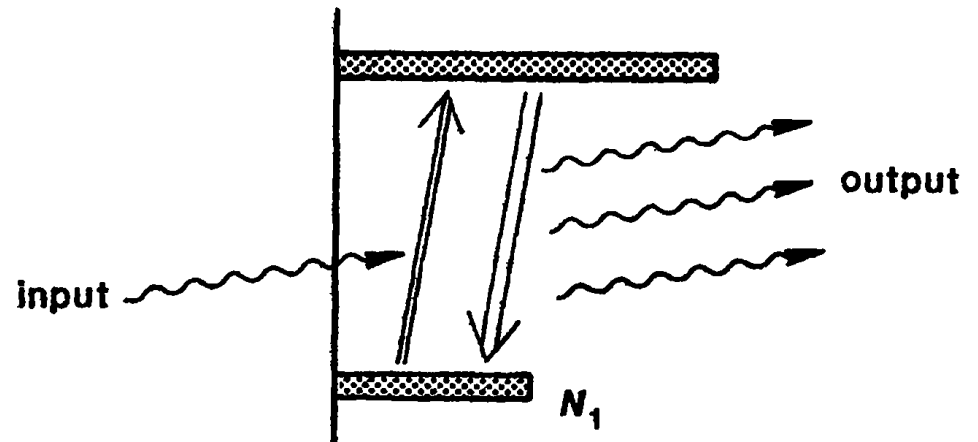
Energy Levels Population Inversion

during the pumping process
in suitable medium level
population can be inverted

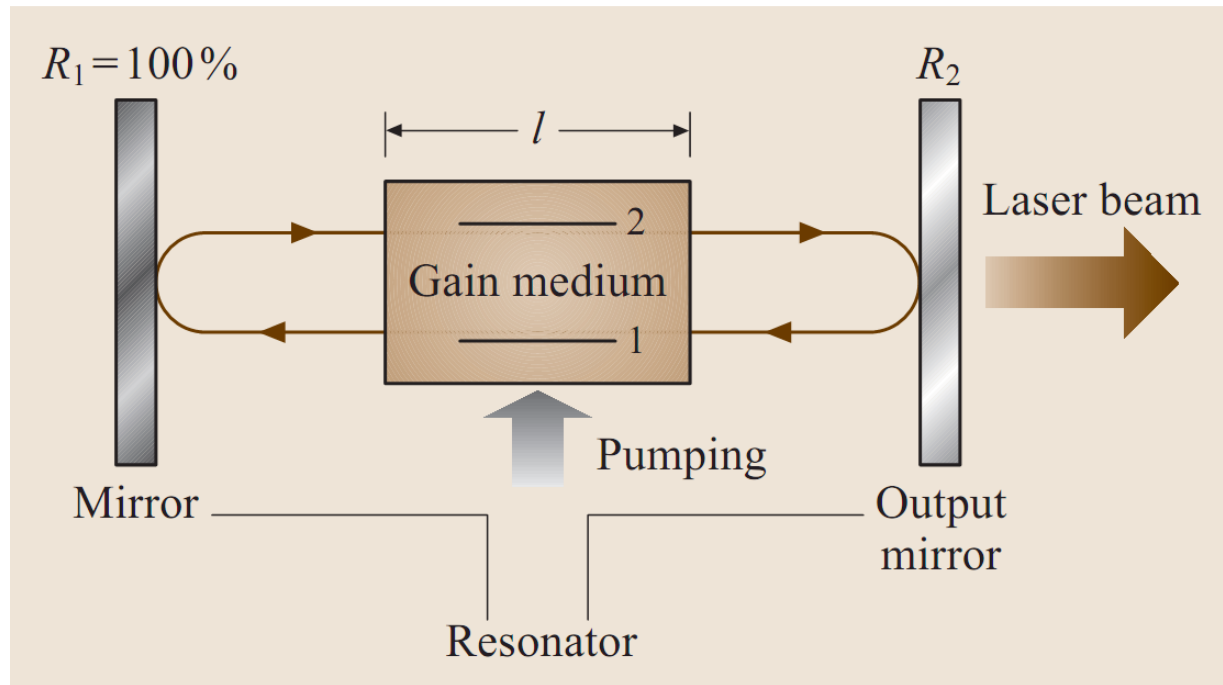


so that stimulated emission rate is
higher than absorption rate (which
is still present)

⇒ in total, light amplification takes
place



Scheme of Laser

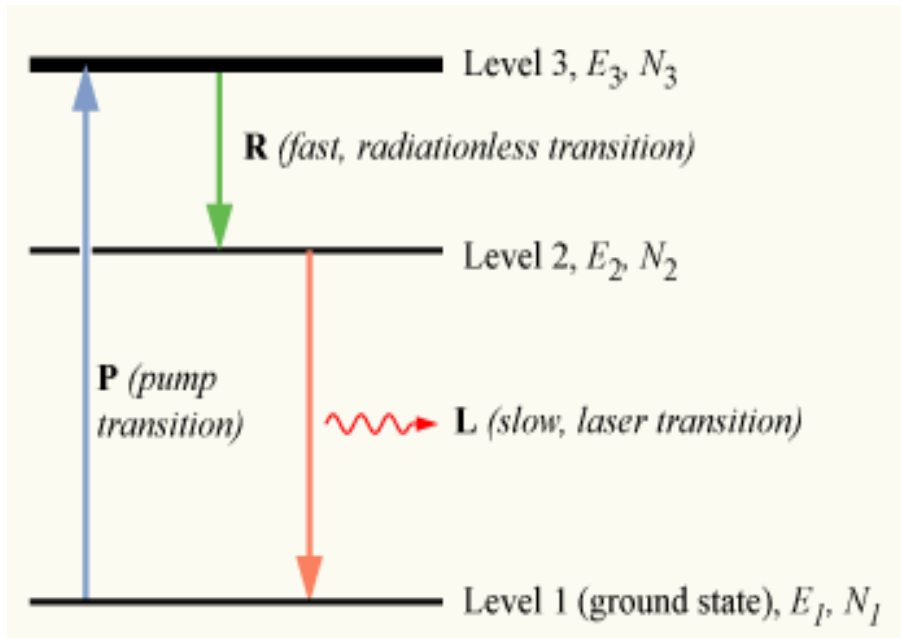


Three key elements of the laser:

- **laser medium** (active medium) to store the energy
- **laser resonator** (mirrors) = feedback
- **pumping** = energy supply

Laser Medium

- Solid insulator: $\text{Nd}^{3+}:\text{YAG}$, $\text{Yb}^{3+}:\text{YAG}$ $\text{Ti}^{3+}:\text{Al}_2\text{O}_3$ (Ti:Sapphire), $\text{Cr}^{3+}:\text{Al}_2\text{O}_3$ (ruby)
- Semiconductor: GaN-AlN, GaAs-AlGaAs, GaP,
- Gas: He-Ne, CO_2 , Kr, $\text{Kr}+\text{F}_2$...
- Liquid: organic dyes, ... (*practically not so important.*)



Laser medium need to have certain energy level structure to fulfil following functions:

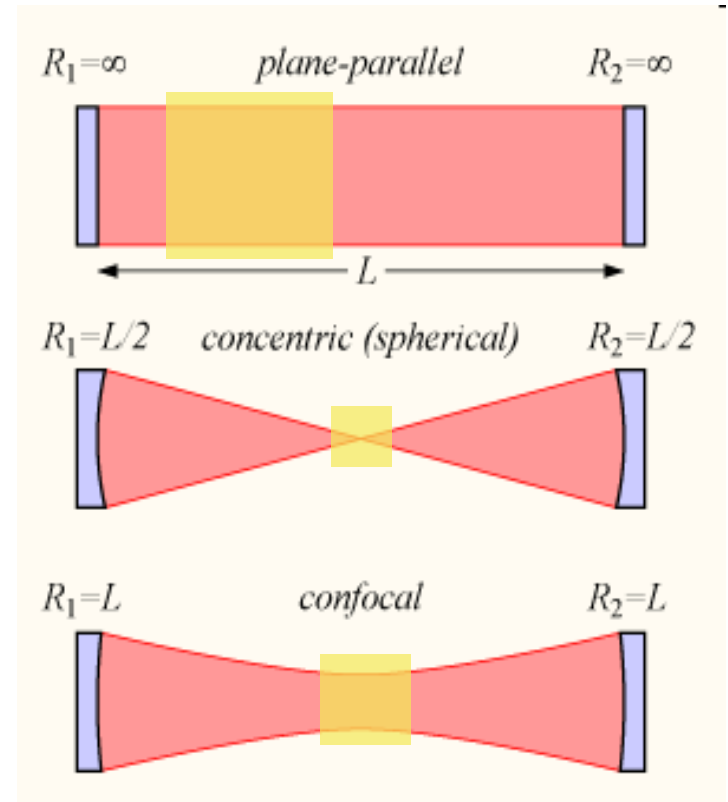
- **absorb and store** energy
- **create conditions for stimulated emission – level population inversion**

Resonator

Main function of the resonator is to provide feedback = some light is reflected back as a seed for stimulated emission:

- to be **amplified** again in the laser medium
- to provide **information on frequency, phase, direction** – reason for special light properties

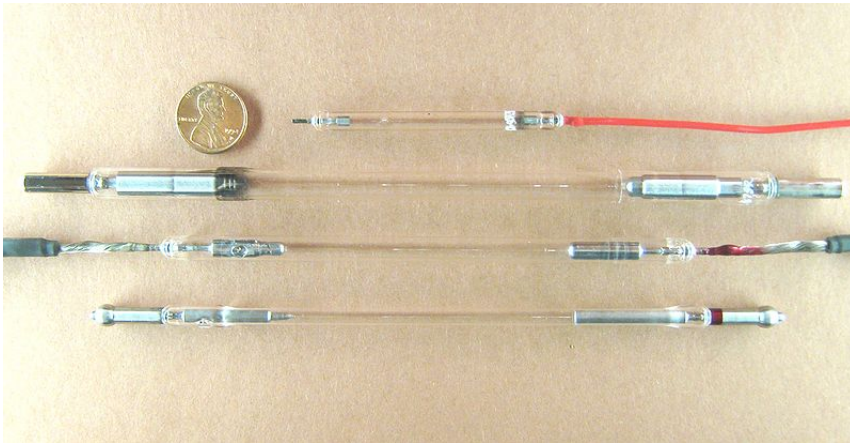
Examples:



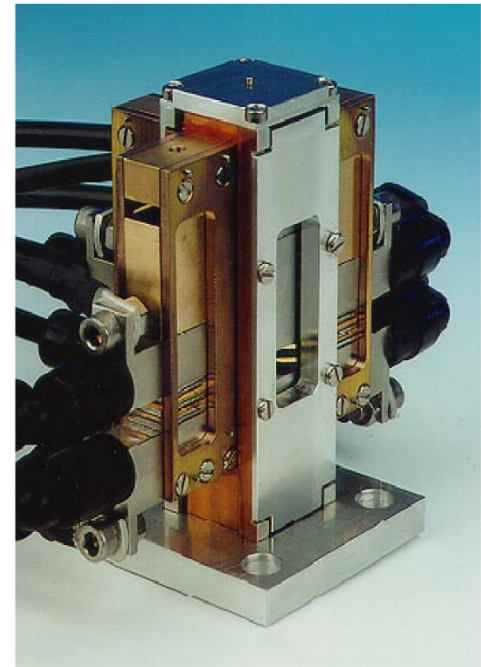
The configuration of the resonator strongly depends on the laser type and desired light properties.

Optical Pumping

- Laser medium absorbs light of:
 - gas discharge lamps (flash or continuous)
 - another laser (e.g. laser diodes)



T-Stack



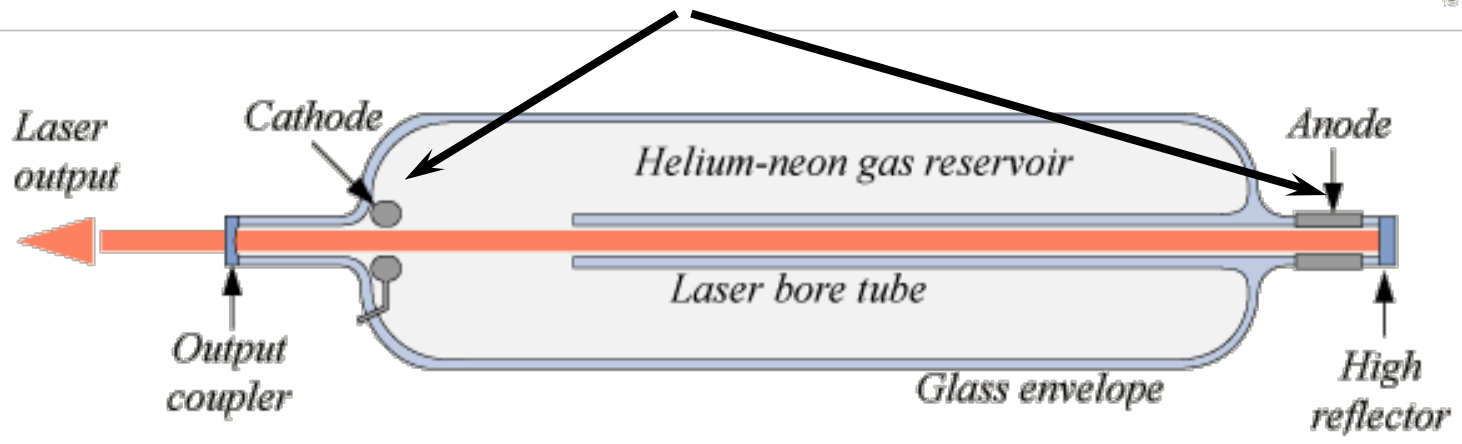
Electric Pumping

- electric current (creating e-h pairs in semiconductors)
- gas discharge (excimers, CO₂, He-Ne)

exciting by flowing current



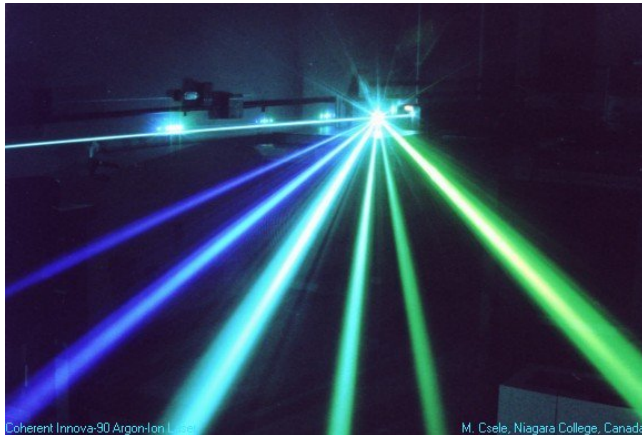
gas discharge take place
between the electrodes



Gas Lasers

- Argon : 364 nm, 488 nm, 514 nm
- Krypton : 647 nm (+ other visible lines)

Argon

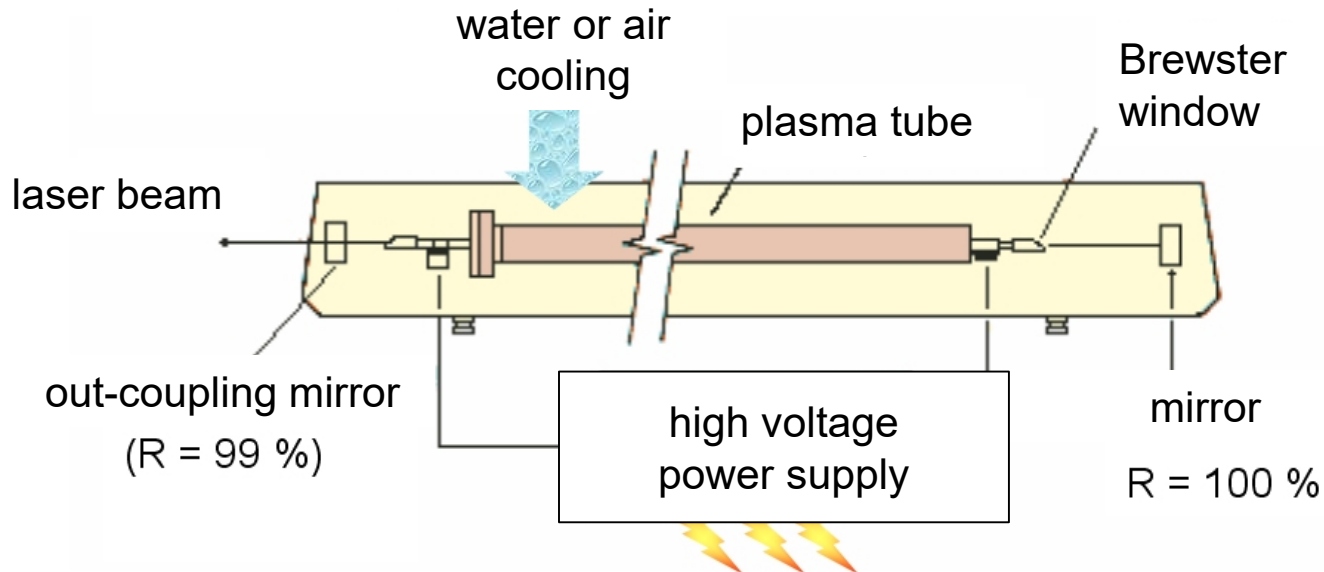


Argon + Krypton



Gas Lasers

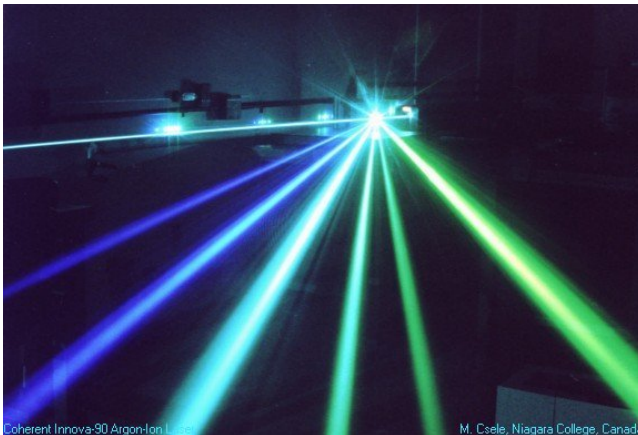
- Active medium = ionised gas (Ar, Kr...)
- Pumping = electrical discharge
- Resonator = usually plane parallel



Gas Lasers

- continuous wave (not pulsed)
- very high beam quality
- relatively low power – tens of W
- inefficient ($<1\%$) – high heat generation

Argon



Argon + Krypton

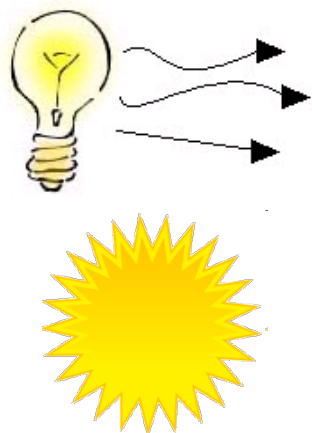
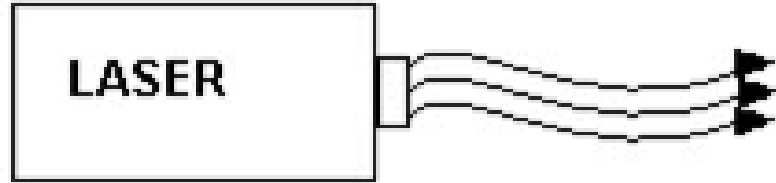


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- **Properties of Laser Light**
- Laser Types
- Pulsed Lasers
- Light Emitting Diodes (LEDs)

Properties of Laser Radiation

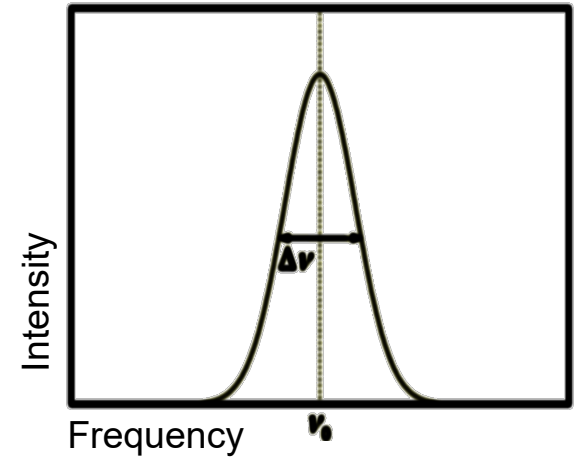
- monochromatic
- coherent
- directed
- high brightness / high beam quality



- multiple wavelength (colors)
- incoherent
- omnidirectional
- low brightness

Light Monochromaticity

typical laser emits light in narrow wavelength range
 $\Delta\lambda \sim 0.0001 \text{ nm} - 1 \text{ nm}$

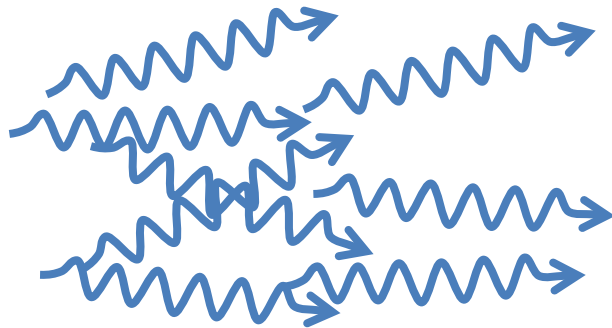


- spectral line width ($\Delta\lambda$) of the laser depends on:
- emission (gain) spectrum of the laser medium
 - transmission spectrum of the resonator
 - resonator quality = how many times light travels around in resonator

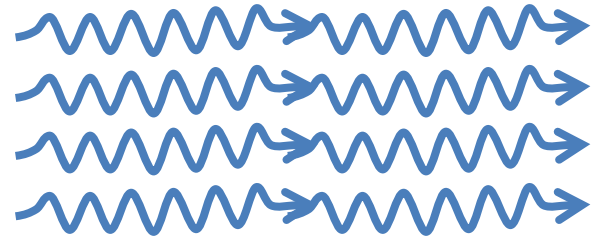
Coherency

- Single photon in incoherent light are not correlated
- For coherent light, phases of the photons (EM-waves) are correlated both in space and in time

Incoherent light source



Coherent light source



Brightness/Radiance of a Laser

- **Brightness** is a qualitative term.
- **Radiance** should be used for quantitative expressions

Radiance – **power** emitted per unit **surface** into the unit of **solid angle** $[\text{W}/(\text{m}^2 \cdot \text{sr})]$

Emitting surface - laser beam cross-section at the exit

Emission angle - divergence of laser beam

Divergence of laser beam is typically very low \Rightarrow **brightness** (radiance) is very high

Beam Quality - Beam Brightness

for 'ideal' laser beam
(Gaussian beam)

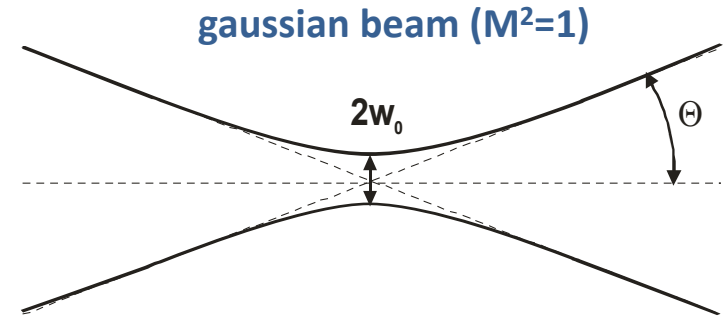
$$\theta = \frac{\lambda}{w_0 \pi}$$

for non-ideal beam an M^2 -factor is introduced

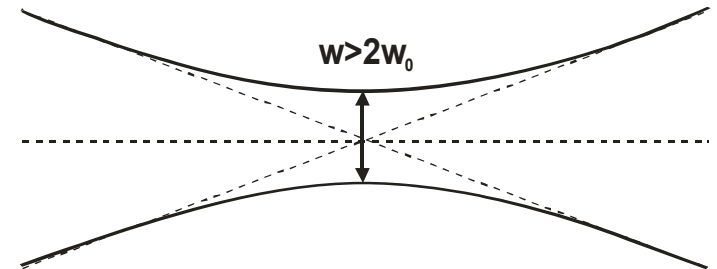
$$\theta = M^2 \frac{\lambda}{w_0 \pi}$$

Radiance/Brightness is inversely related to beam quality

$$B = \frac{P}{\pi w_0^2 \pi \theta^2} = \frac{P}{M_x^2 \cdot M_y^2 \cdot \lambda^2}$$

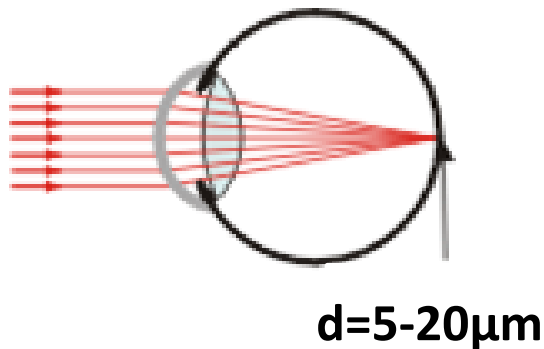


worse quality beam can not be focused as good with the same optics

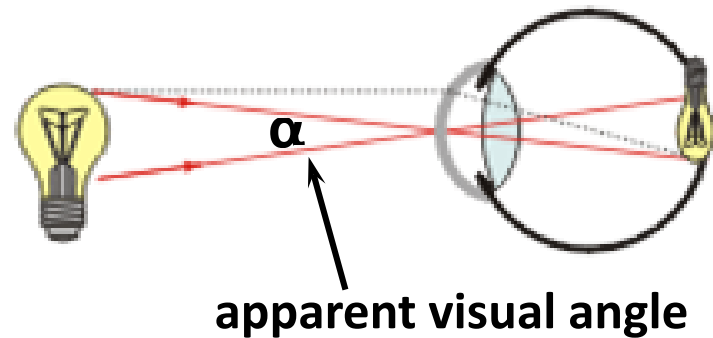


Laser vs. Conventional Light Sources

laser beam can be focused
to very small area on the retina
(high brightness beam)



power of conventional (low brightness)
light sources is distributed
over quite large area



Radiance (brightness) of Sources

- Comparative radiance (brightness) of light sources:

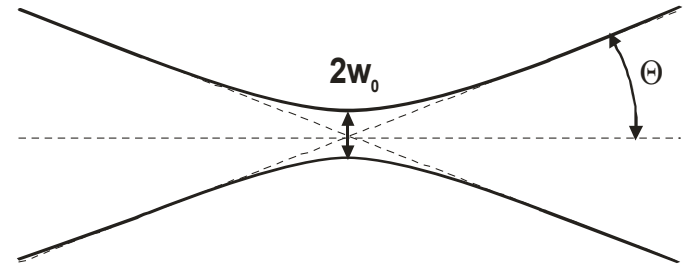
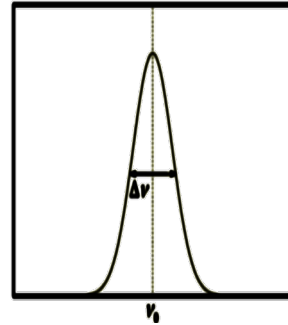
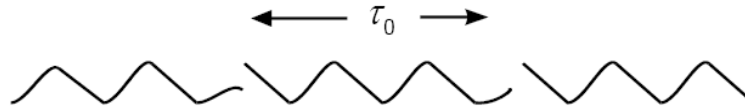
Sun	$\sim 1.5 \times 10^7 \frac{W}{sr \cdot m^2}$
1 mW laser	$\sim 3 \times 10^9 \frac{W}{sr \cdot m^2}$
1 W laser	$\sim 3 \times 10^{12} \frac{W}{sr \cdot m^2}$

Irradiance on the eye retina is proportional to the radiance (brightness) of the source:

- 1 mW laser already gives 100 times (two orders of magnitude!) higher power density (W/m^2) than staring in the sun.
- 1 W laser - 100 000 times (five orders!) higher power density

Properties of Laser Radiation

- monochromatic
- coherent
- directed
- high brightness / high beam quality

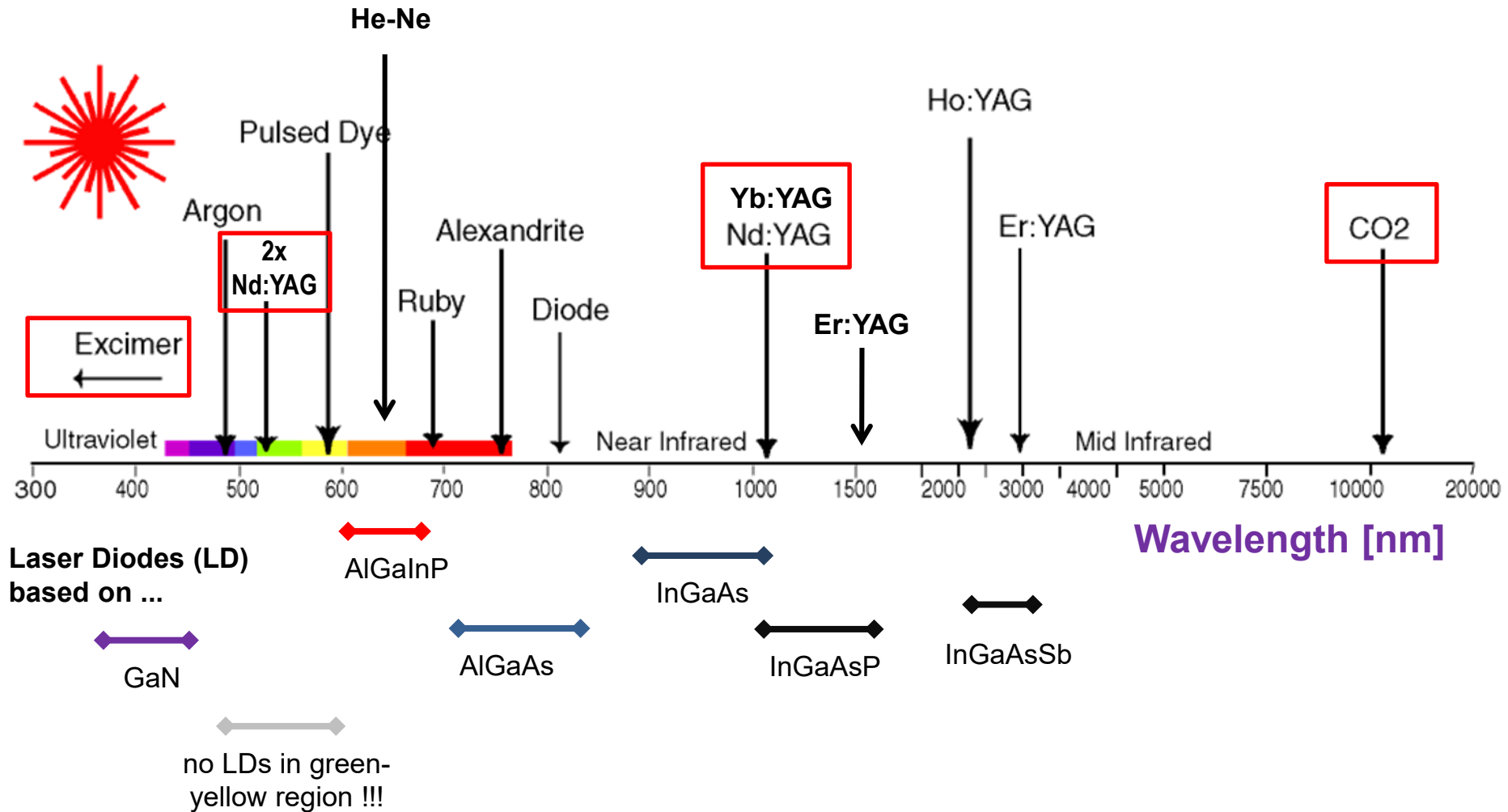


High brightness of (directed) laser beam is the main reason for its danger for the eyes !!!

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Laser Types: wavelength

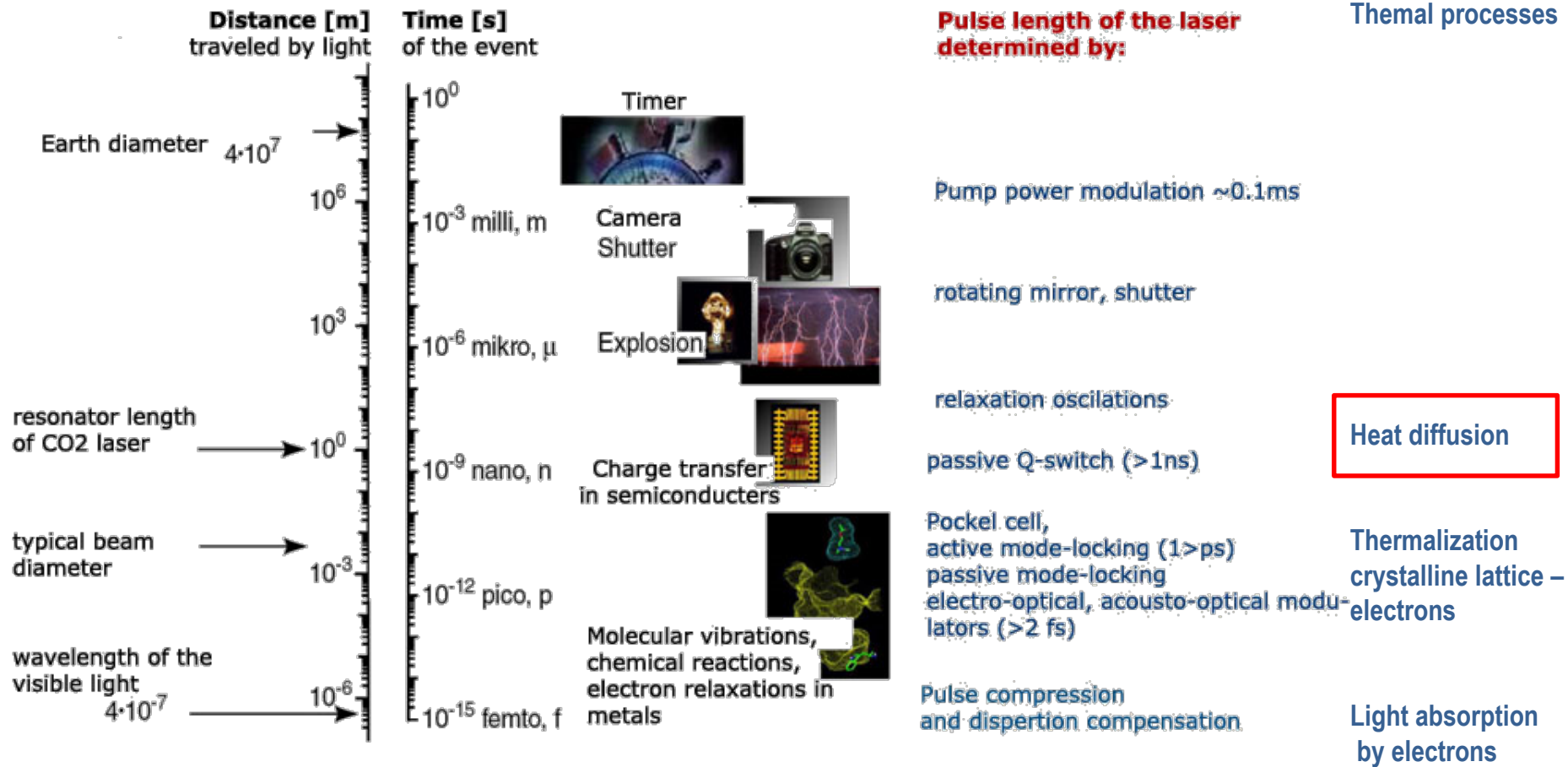


used for laser processing

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Time Scales



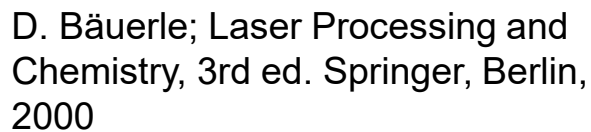
Laser Types: Pulsed & CW

Type of laser	Pulse length determined by	Typical pulse length	Characteristic pulse peak power
Continuous wave (cw)	-	∞	Ws – kWs
Free running laser	Pump pulse length (flash lamp)	100 μ s – 1ms	kWs
Q-switched laser	Time constants of active material and modulating element	1 ns – 100 ns	MWs
Mode-locked laser	Number of coupled modes, pulse compression	10 fs – 10 ps	GWs

What each type of the laser is good for ?

1) **time scale** of the process

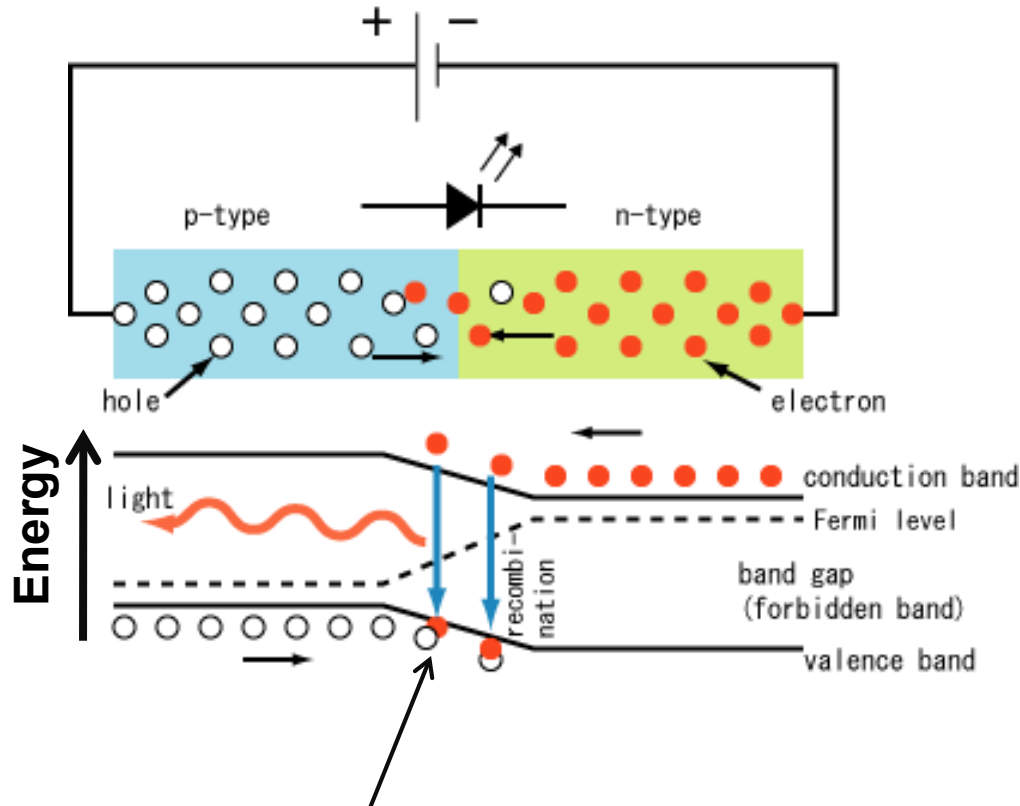
2) **intensity** you need for the process



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Light Emitting Diodes



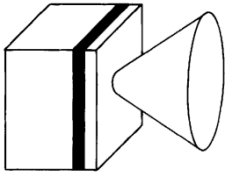
Recombination of electrons and holes in the p-n junction liberates energy, emitted as light.

Differences between LED and LD (laser diode):

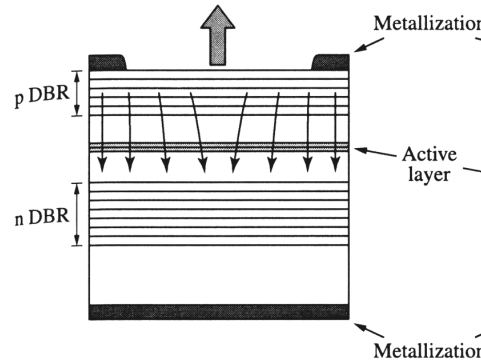
- LED devices do **not** reach light amplification condition
- LD have designed resonator (feedback) to promote **stimulated emission**
- LED are **spontaneous emission devices**
- LD emission is more directed

Light Emitting Diodes

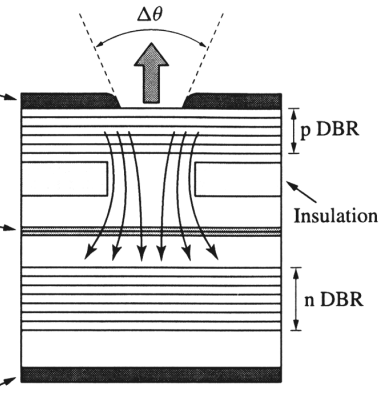
Surface emitting LEDs



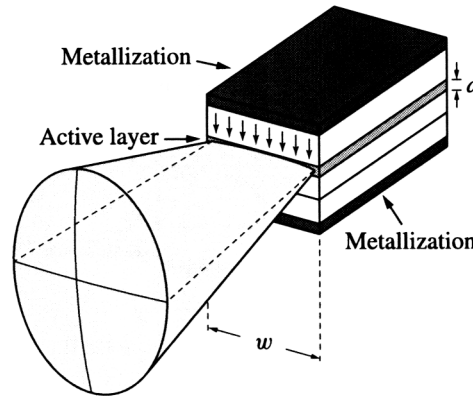
Broad area surface emission



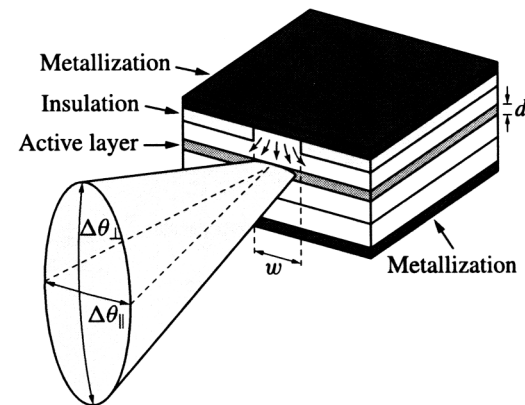
small area surface emission



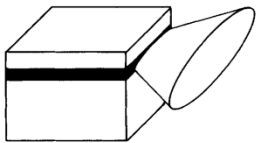
Broad area edge emission



Strip geometry edge emission



Edge emitting LEDs



Emitting surface of the LED can be quite small:

dia. ~10 μm – for surface emission

1 μm x 10 μm – for edge emitting LED