Empa
Materials Science and Technology

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

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)**.

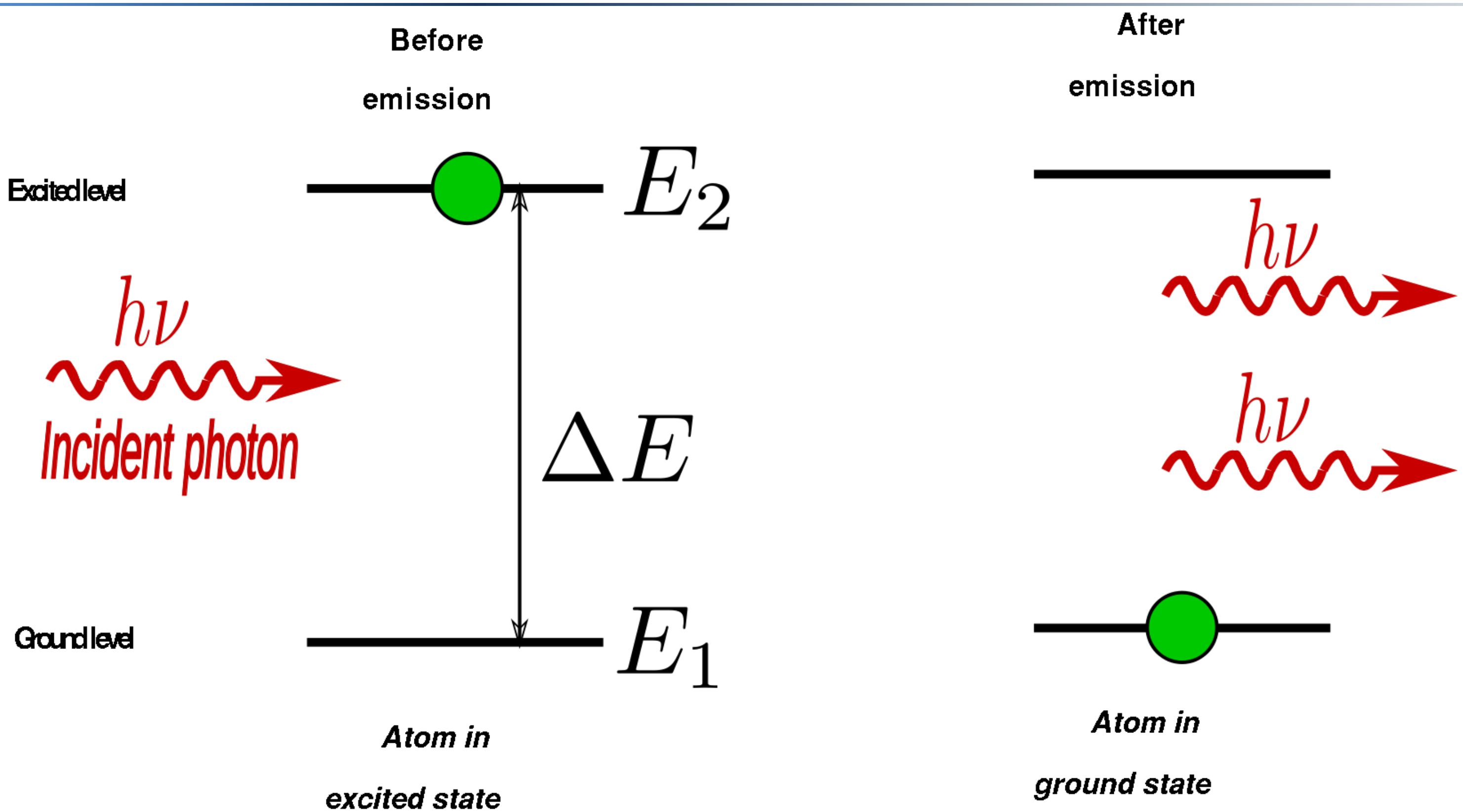
Lasers. by **Anthony E. Siegman**. **(Univ Science Books, 1986)**

Key Concepts/Elements

What is ...?

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

Stimulated Emission

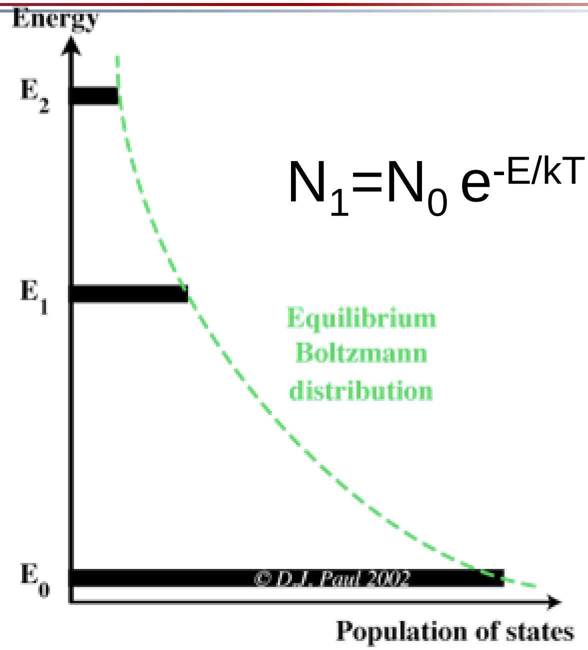


Frequency, Phase, Direction of stimulated emission photon are identical to that of the incident photon

$\Rightarrow$ reason for the special properties of the laser light

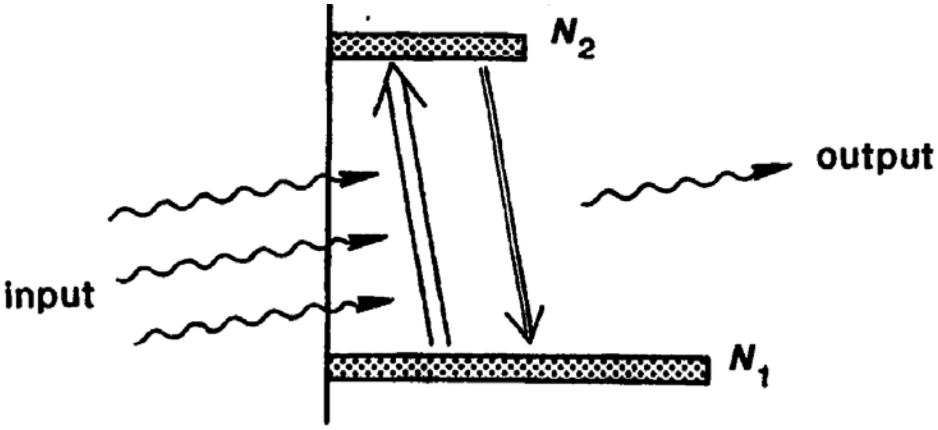
Energy Levels Population Inversion

normally energy levels are populated according to Boltzmann distribution



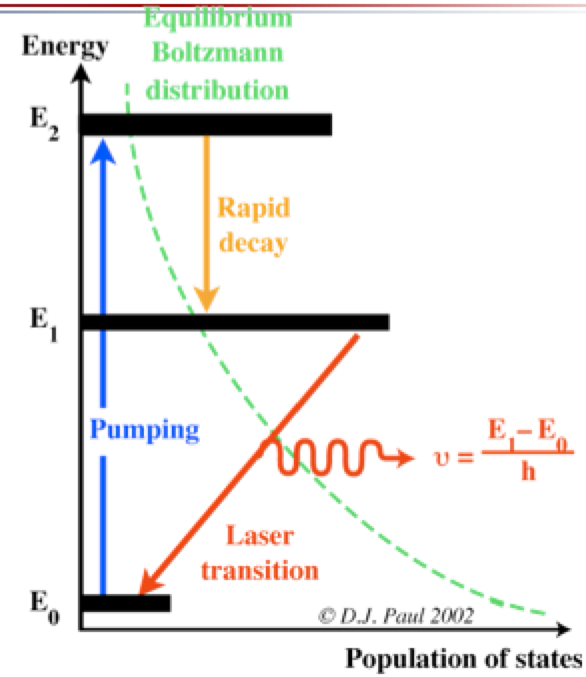
$$N_1 = N_0\, e^{-E/kT}$$

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



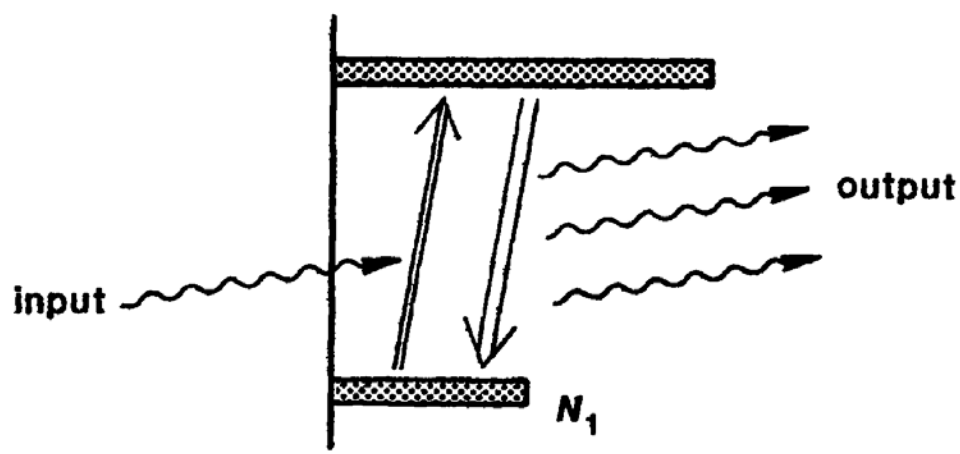
Energy Levels Population Inversion

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

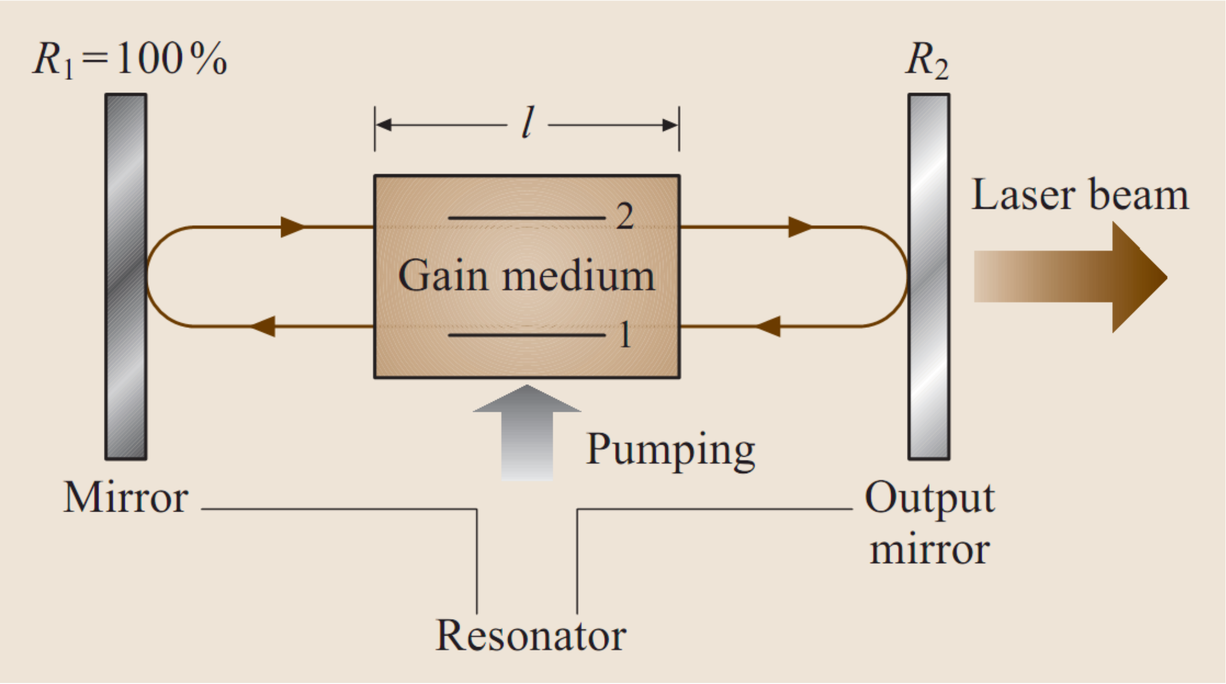


so that stimulated emission rate is higher than absorption rate (which is still present)

⇒ in total, light amplification takes place



Scheme of Laser

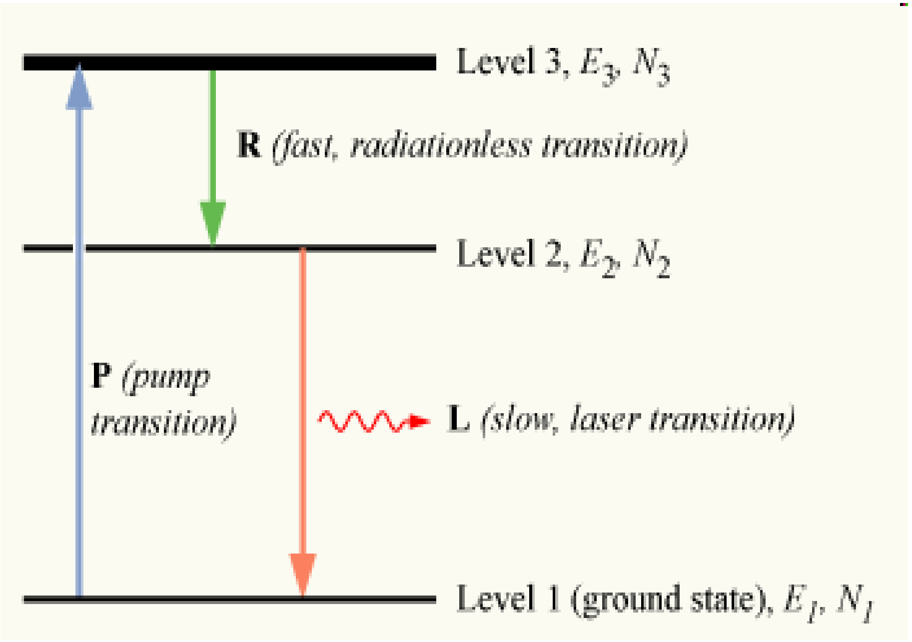


Three key elements of the laser:

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

Laser Medium

- Solid insulator: Nd^{3+}:YAG, Yb^{3+}:YAG $Ti^{3+}:Al_2O_3$ (Ti:Sapphire), $Cr^{3+}:Al_2O_3$ (ruby)
- Semiconductor: GaN-AlN, GaAs-AlGaAs, GaP, ….
- Gas: He-Ne, CO_2, Kr, Kr+F_2 …
- Liquid: organic dyes, … *(practically not so importnant.)*



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

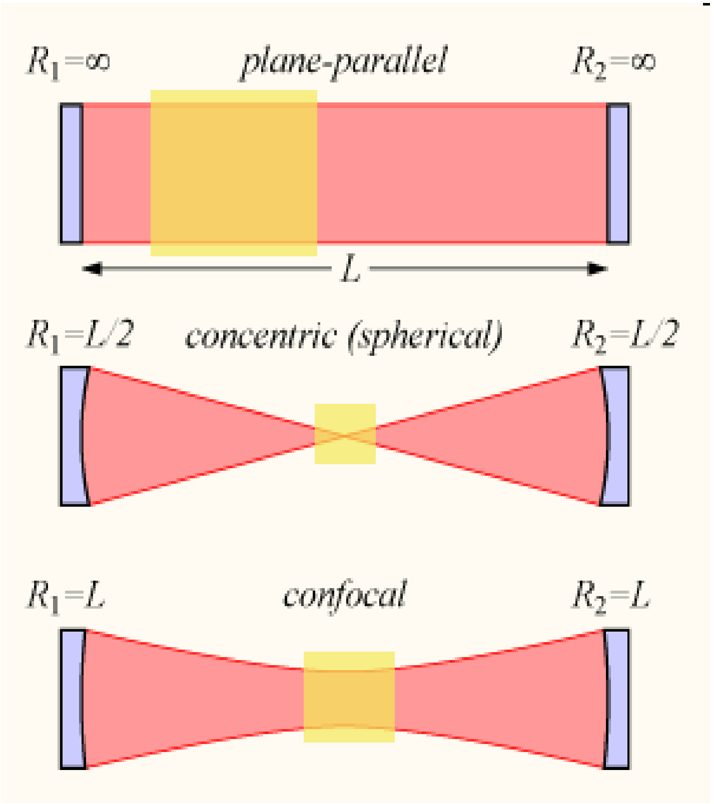
- **absorb and store energy**
- **create conditions for stimulated emission – level population inversion**

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**

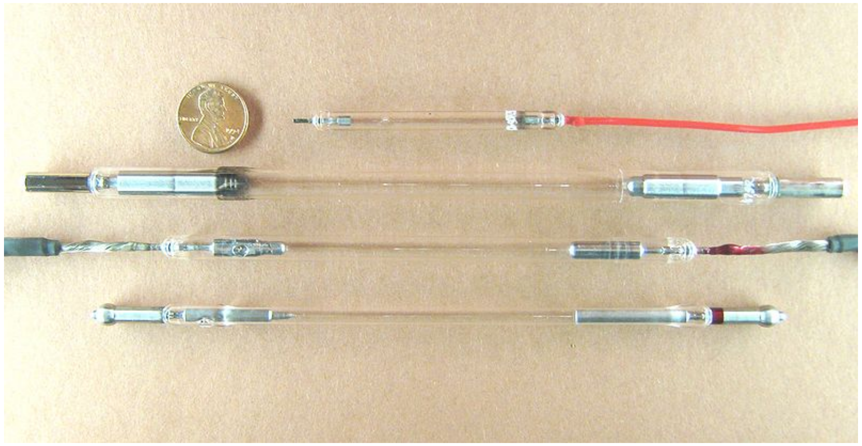
Examples:



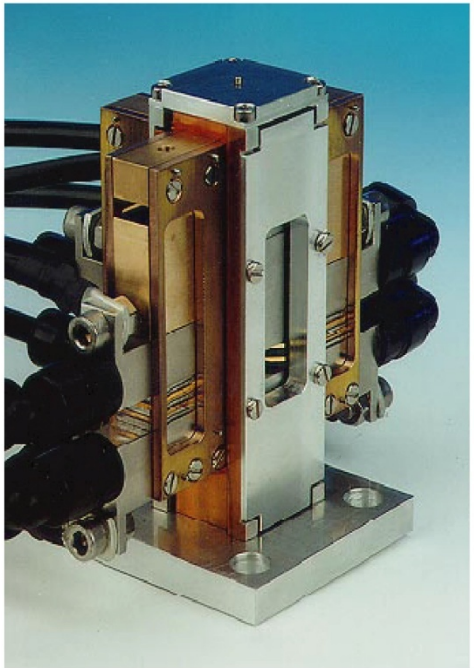
The configuration of the resonator strongly depends on the laser type and desired light properties.

Optical Pumping

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



T-Stack



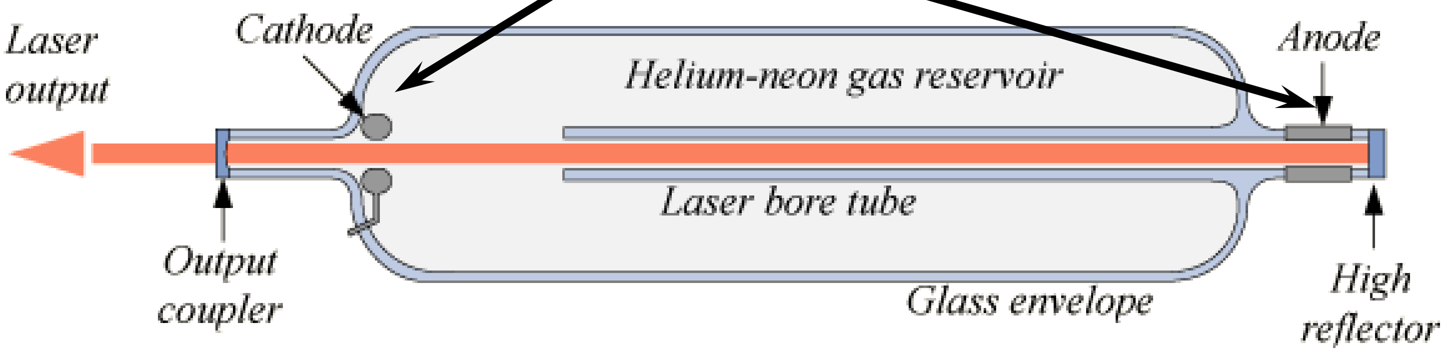
Electric Pumping

– electric current (creating e-h pairs in semiconductors)

– gas discharge (excimers, CO_2, He-Ne)

exciting by flowing current

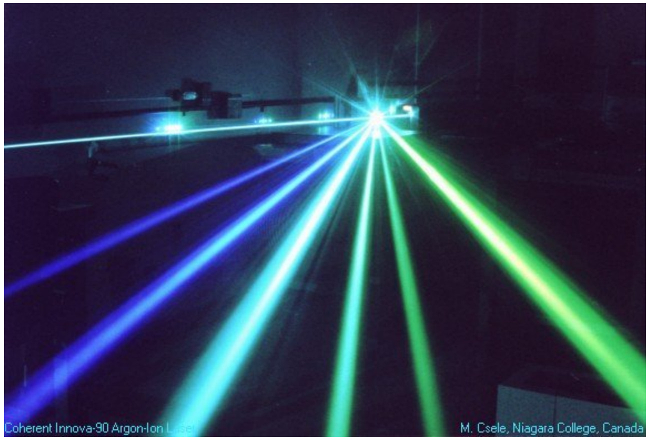
gas discharge take place
between the electrods



Gas Lasers

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

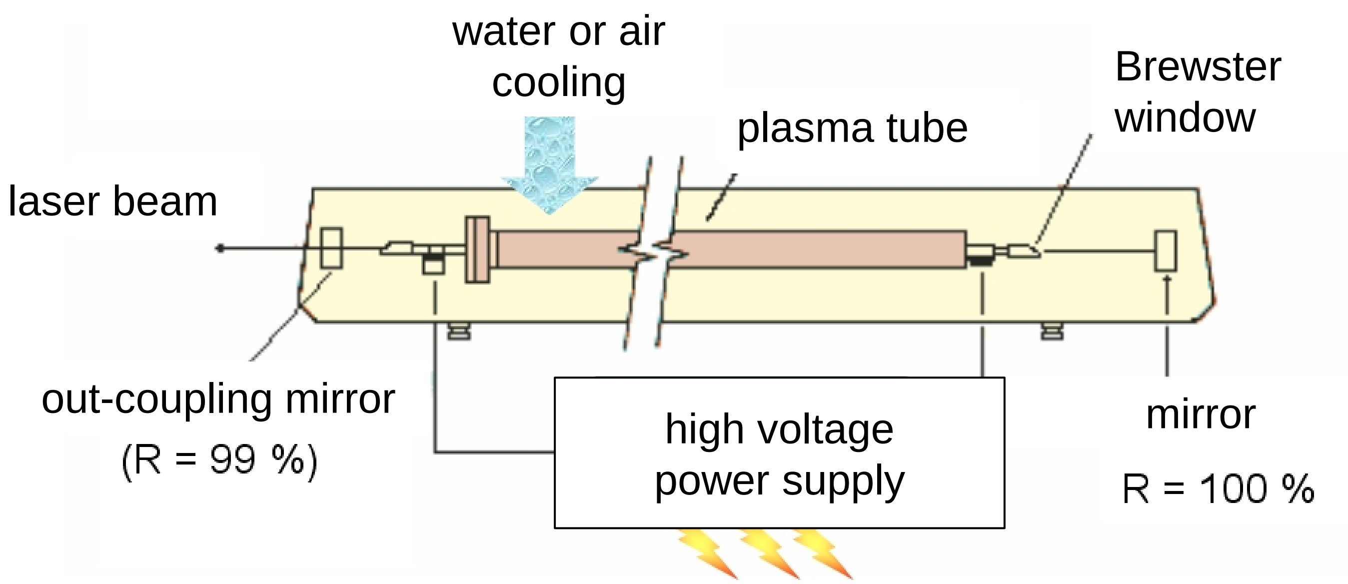
Argon



Argon + Krypton

Gas Lasers

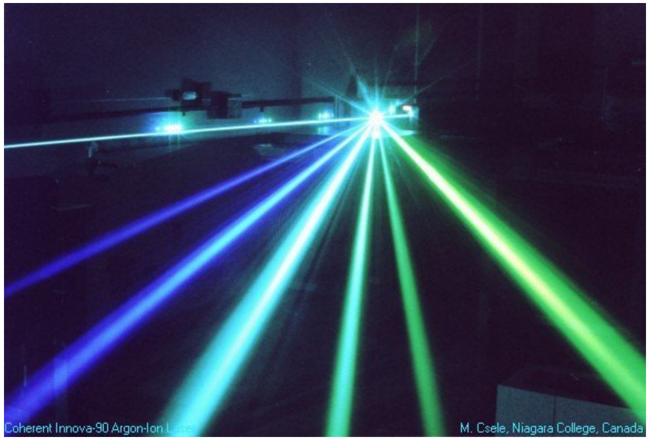
- Active medium = ionised gas (Ar, Kr…)
- Pumping = electrical discharge
- Resonator = usually plane parallel



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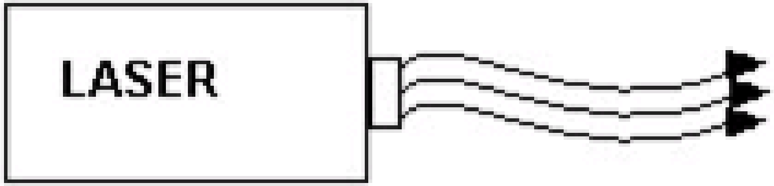
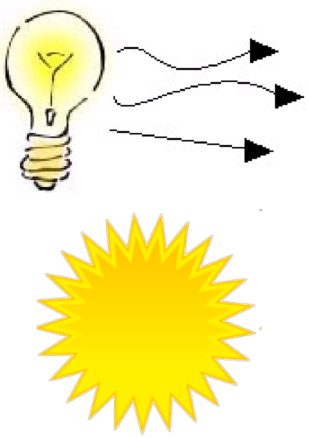
- Laser Principles
- Properties of Laser Light
- Laser Types
- Pulsed Lasers
- Light Emitting Diodes (LEDs)

Propeties of Laser Radiation

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

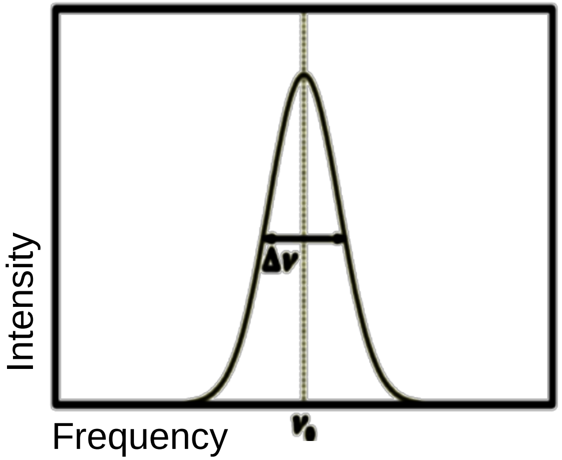




- multiple wavelength (colors)
- incoherent
- omnidirectional
- low brightness

Light Monochromaticity

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



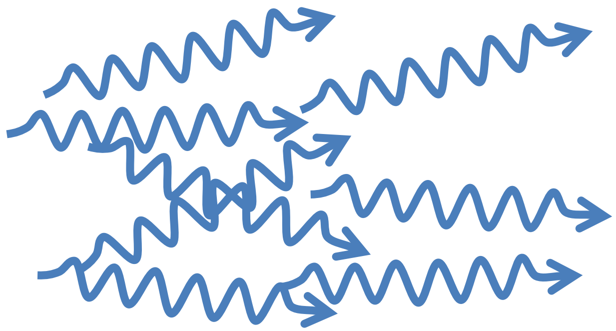
spectral line width ($\Delta\lambda$) of the laser depends on:

- emission (gain) spectrum of the laser medium
- transmission spectrum of the resonator
- resonator quality = how many times light travels around in resonator

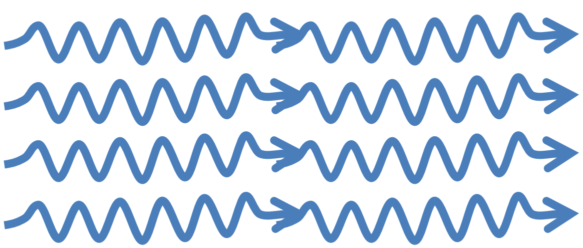
Coherency

- 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 quantative expressions

Radiance – power emitted per unit surface into the unit of solid angle [W/(m^2·sr)]

Emitting surface - laser beam cross-section at the exit

Emision 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)

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

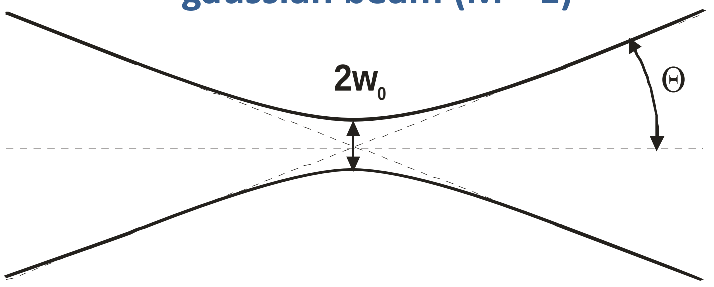
for non-ideal beam an M^2-factor is introduced

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

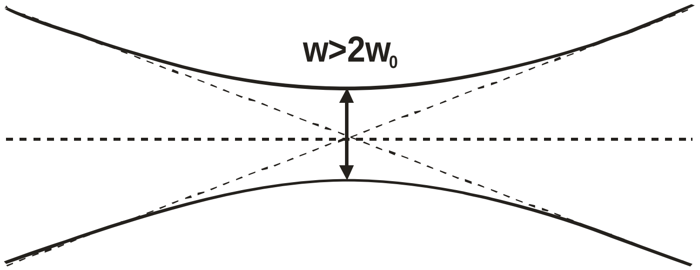
Radiance/Brightness is inversely related to beam quality

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

gaussian beam (M^2=1)



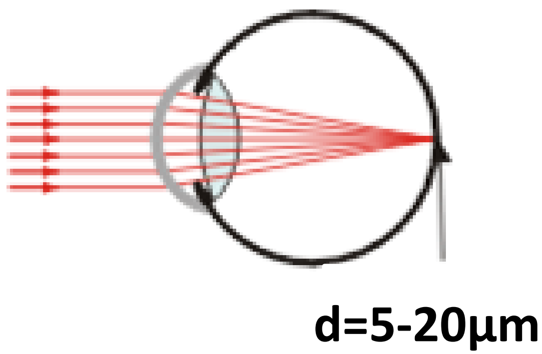
worse quality beam can not be focused as good with the same optics

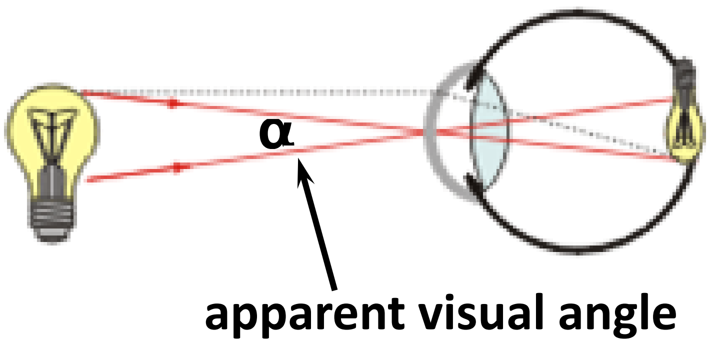


Laser vs. Conventional Light Sources

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:

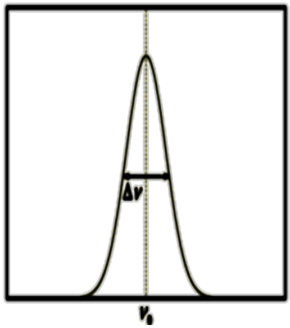
Sun	$\sim 1.5\times10^{7}\,\dfrac{W}{sr\cdot m^{2}}$
1 mW laser	$\sim 3\times10^{9}\,\dfrac{W}{sr\cdot m^{2}}$
1 W laser	$\sim 3\times10^{12}\,\dfrac{W}{sr\cdot m^{2}}$

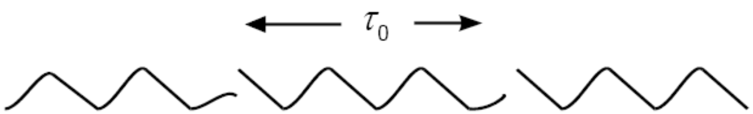
Irradiance on the eye retina is proportional to the radiance (brightness) of the source:

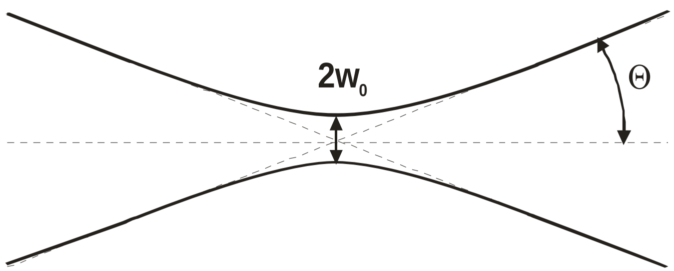
- 1 mW laser already gives 100 times (two orders of magnitude!) higher power density (W/m^2) than staring in the sun.
- 1 W laser - 100 000 times (five orders!) higher power density

Propeties of Laser Radiation

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







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

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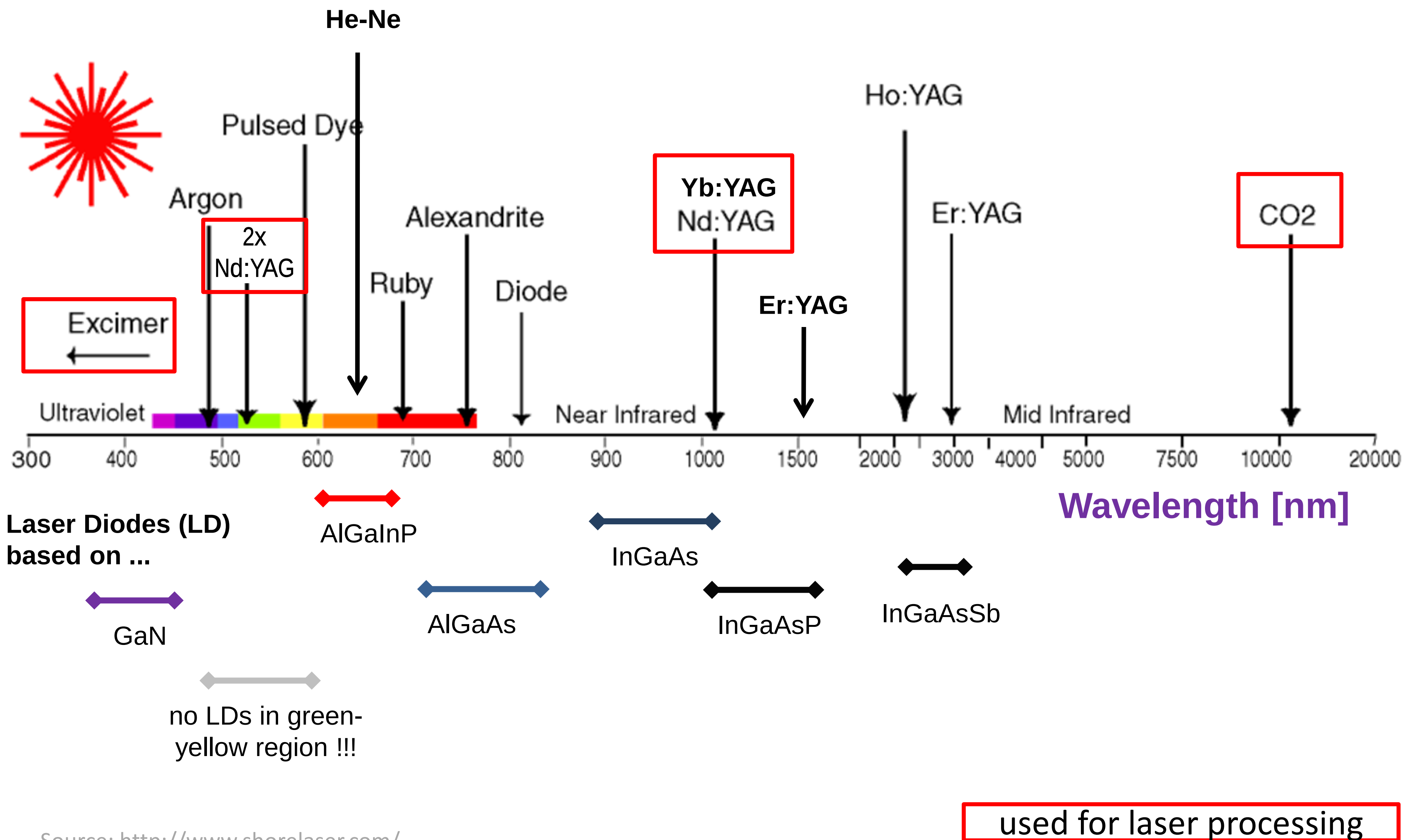
Laser Types: wavelength



Source: http://www.shorelaser.com/

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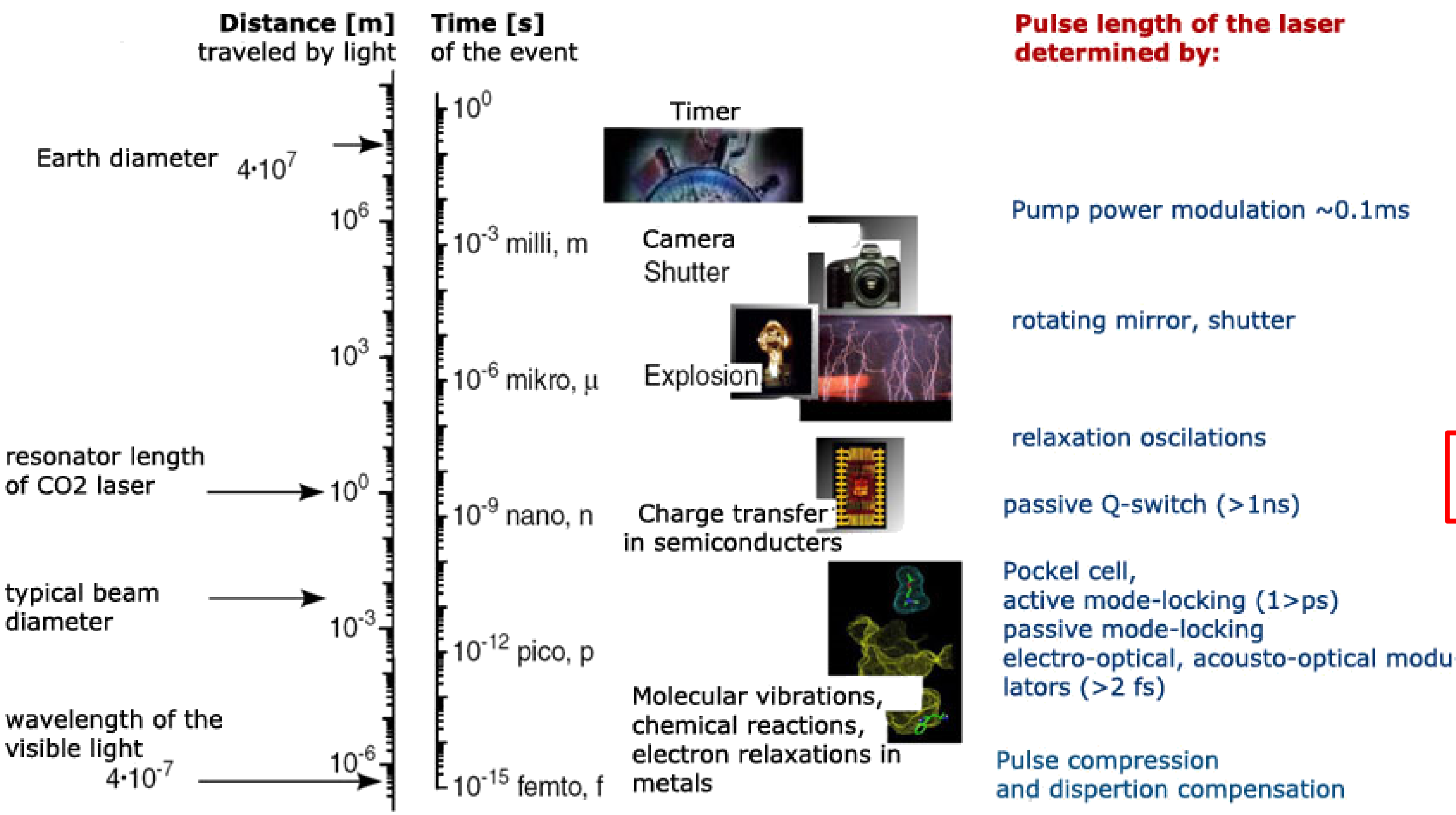
Time Scales



Themal processes

Heat diffusion

Thermalization crystalline lattice – electrons

Light absorption by electrons

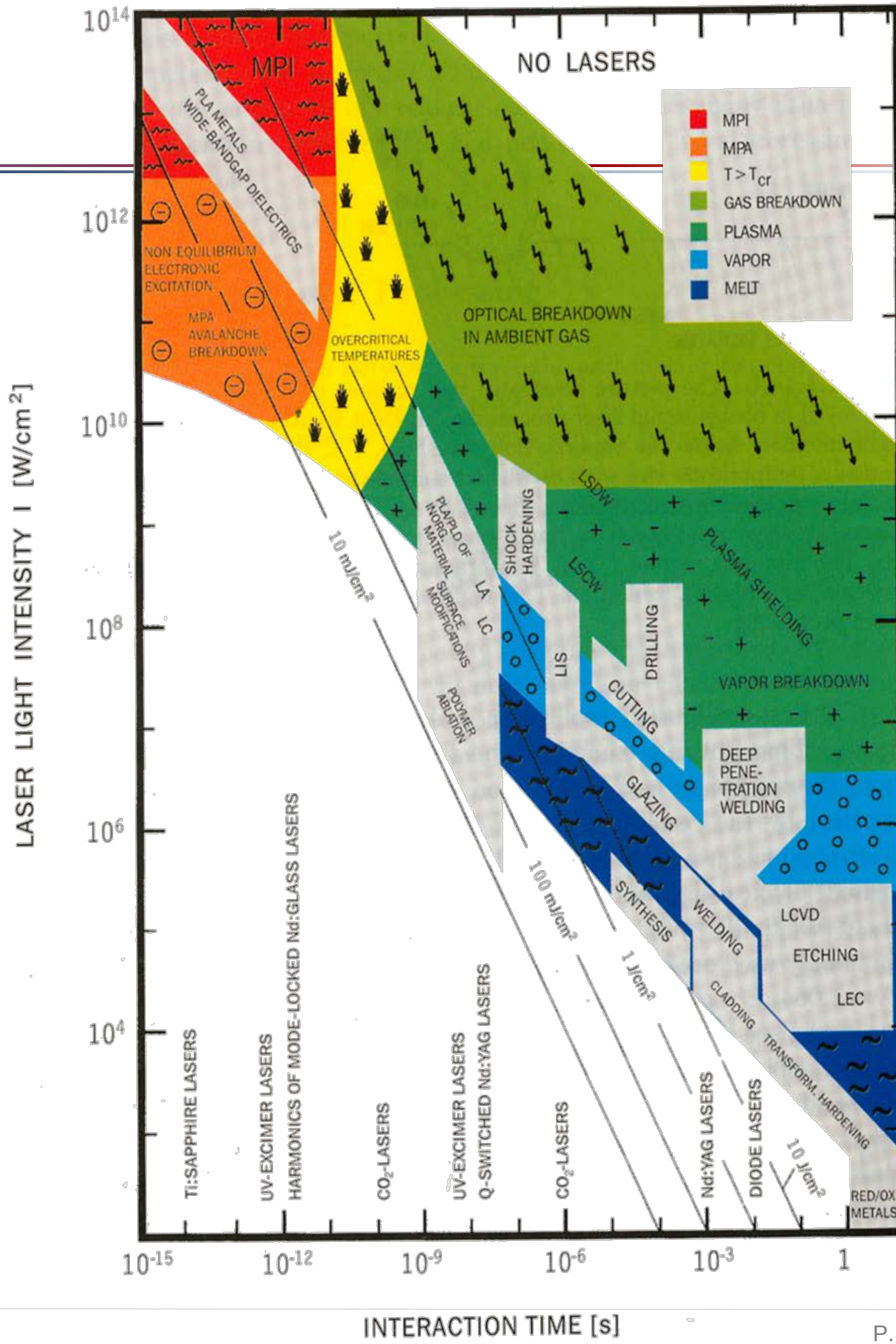
Laser Types: Pulsed & CW

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 µs – 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 ?

It depends on :

1) time scale of the process
2) intensity you need for the process



D. Bäuerle; Laser Processing and Chemistry, 3rd ed. Springer, Berlin, 2000

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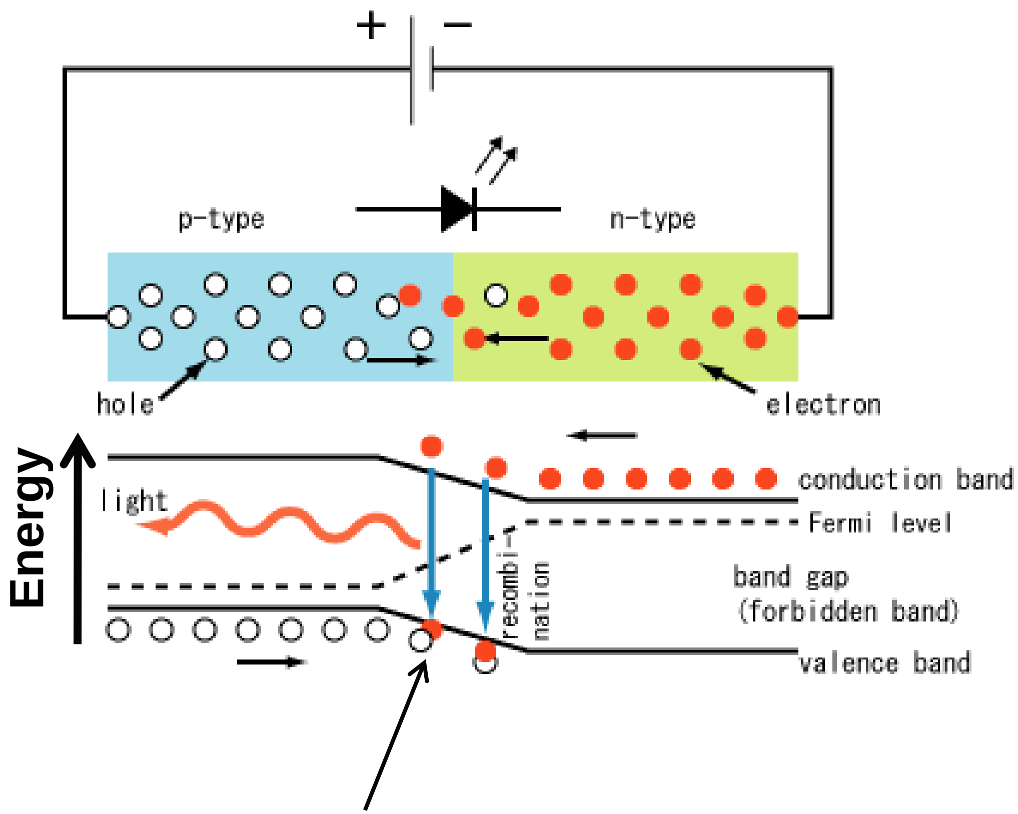
Light Emitting Diodes



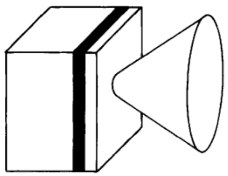
Recombination of electrons and holes in the p-n junction liberates energy, emitted as light.

Differences between
LED and LD (laser diode):

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

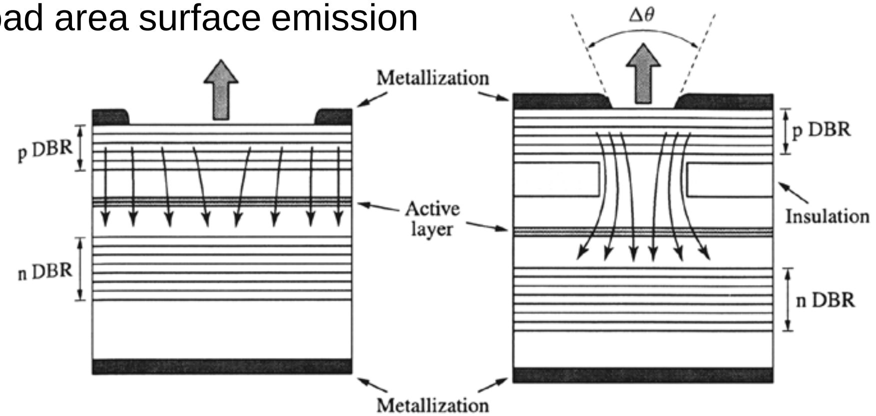
Light Emitting Diodes

Surface emitting LEDs

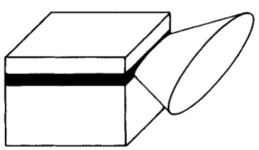


small area surface emission

Broad area surface emission

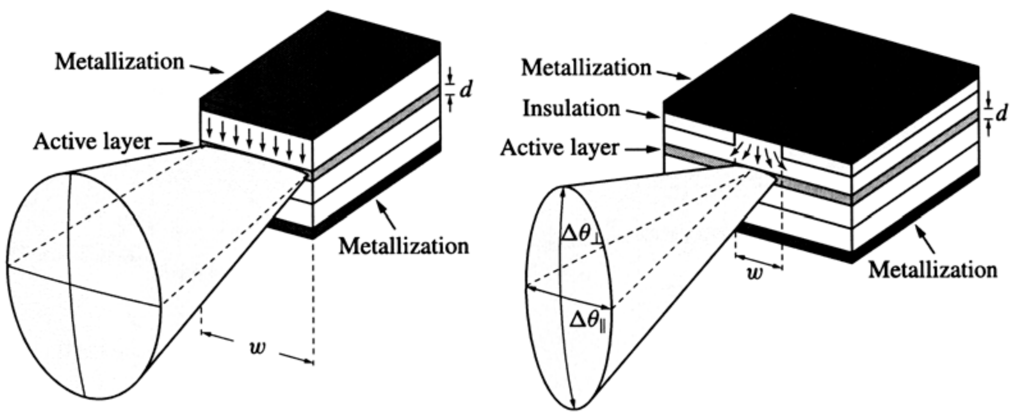


Edge emitting LEDs



Broad area edge emission

Strip geometry edge emission



Emitting surface of the LED can be quite small:

dia.~10 µm – for surface emission

1 µm x 10 µm – for egde emitting LED