Empa
Materials Science and Technology

EPFL

Advanced materials processing with intelligent systems

Lasers, laser safety and beam steering

Sergey Shevchik & Patrik Hoffmann

Content

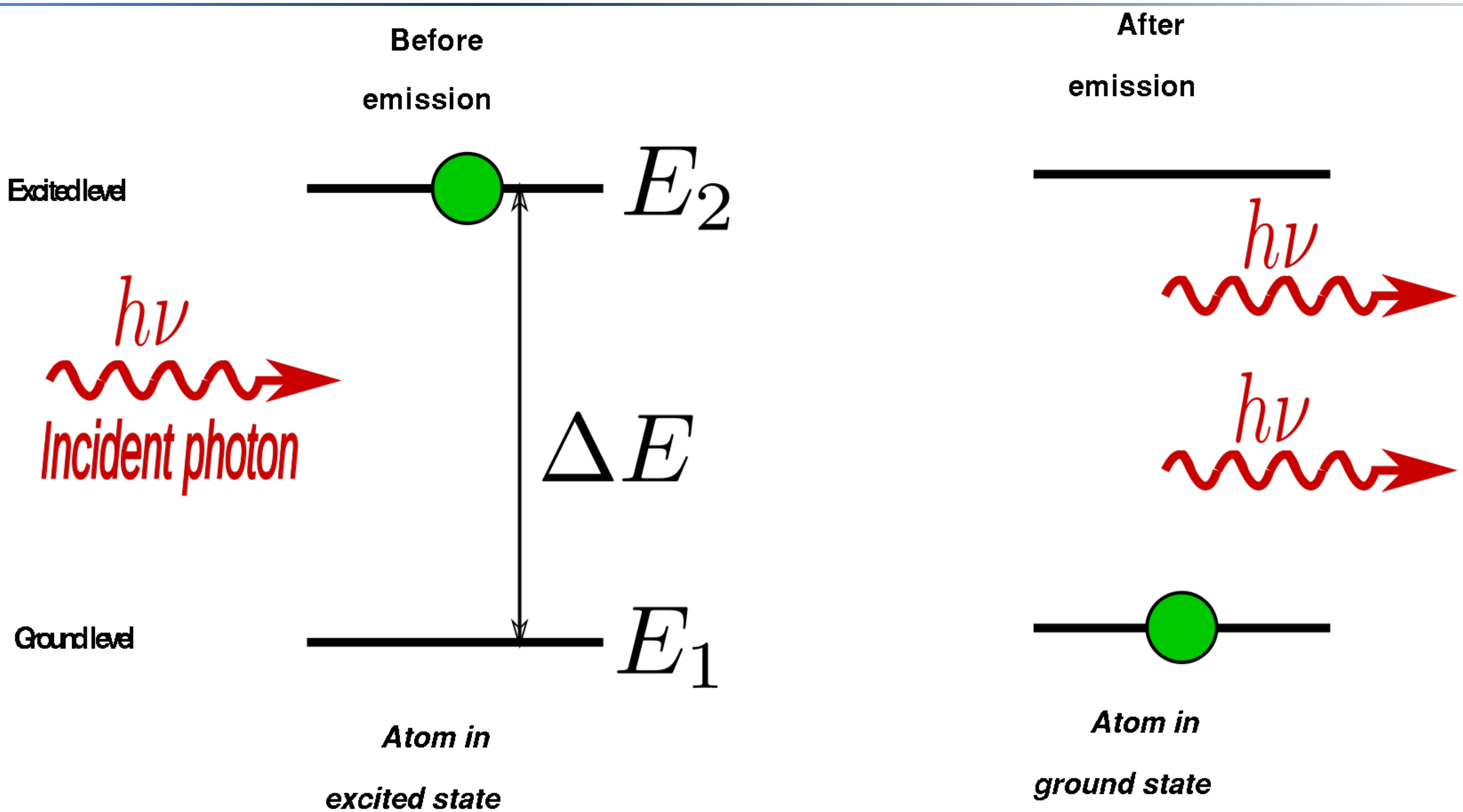
- Laser Principles
- Properties of Laser Light
- Laser Types
- Pulsed Lasers
- Light Emitting Diodes (LEDs)

Key Concepts/Elements

What is …?

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

Stimulated Emission



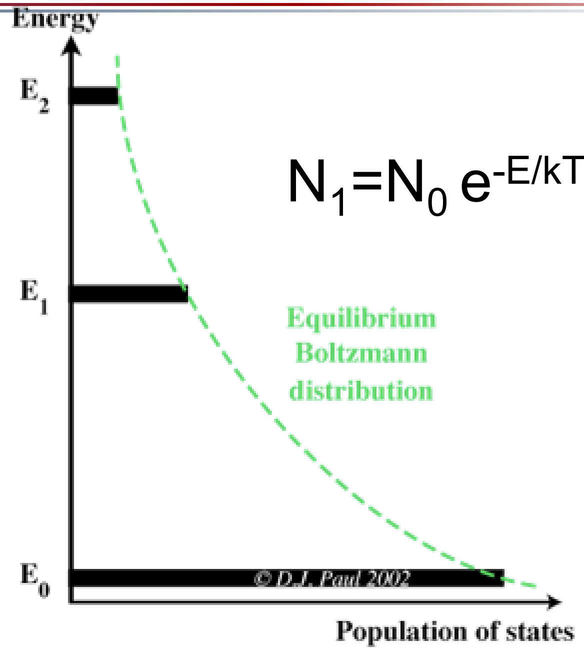
Frequency, Phase, Direction of stimulated emission photon are identical to that of the incident photon

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

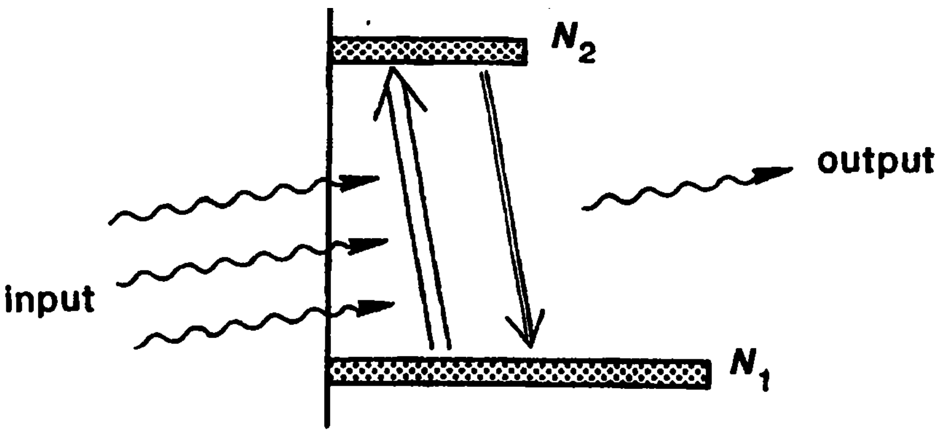
Energy Levels Population Inversion

normally energy levels are populated according to Boltzmann distribution

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

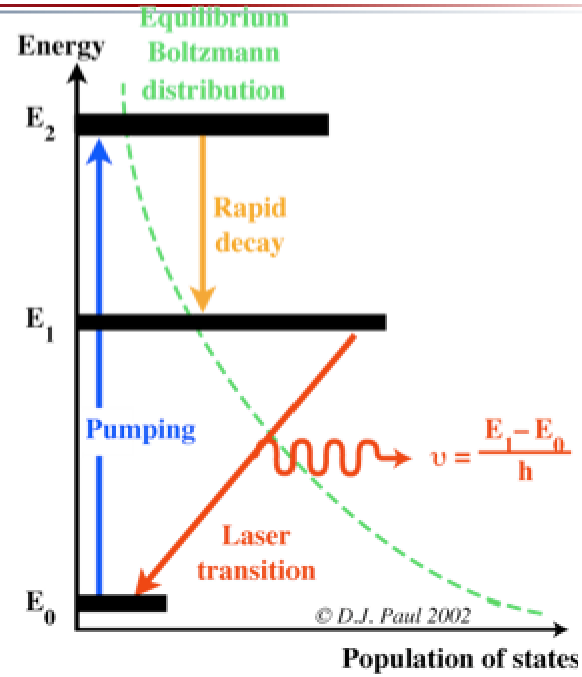


which results in absorption of light prevail over the stimulated emission at transition frequency



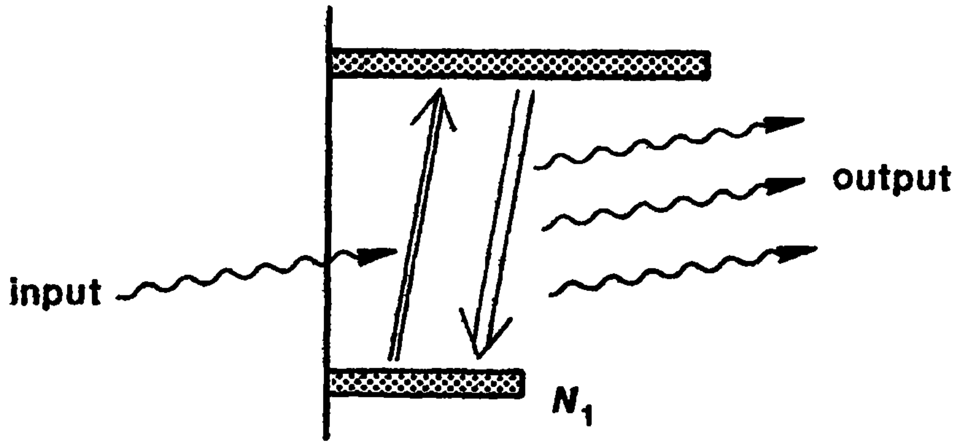
Energy Levels Population Inversion

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

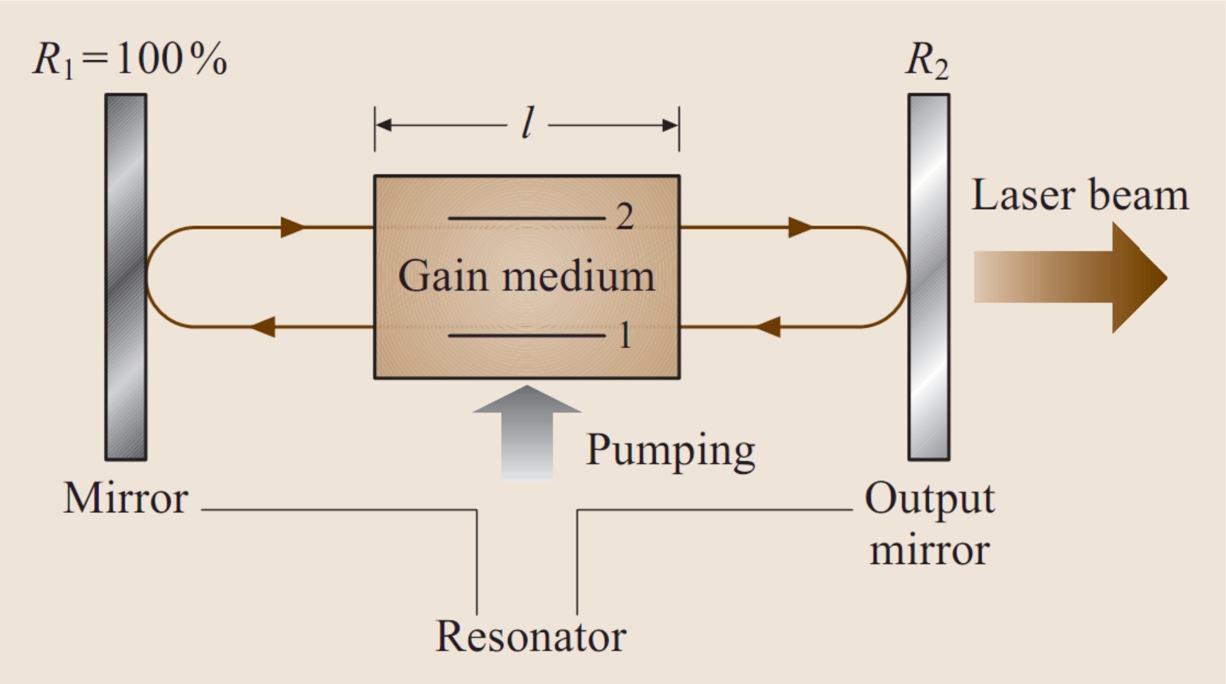


so that stimulated emission rate is higher than absorption rate (which is still present)

⇒ in total, light amplification takes place



Scheme of Laser

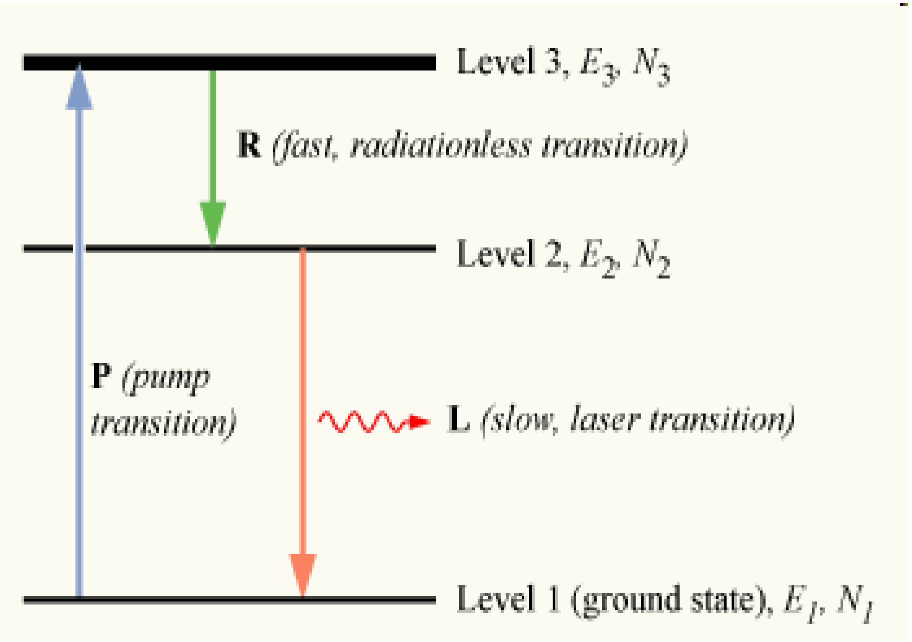


Three key elements of the laser:

- 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.)*



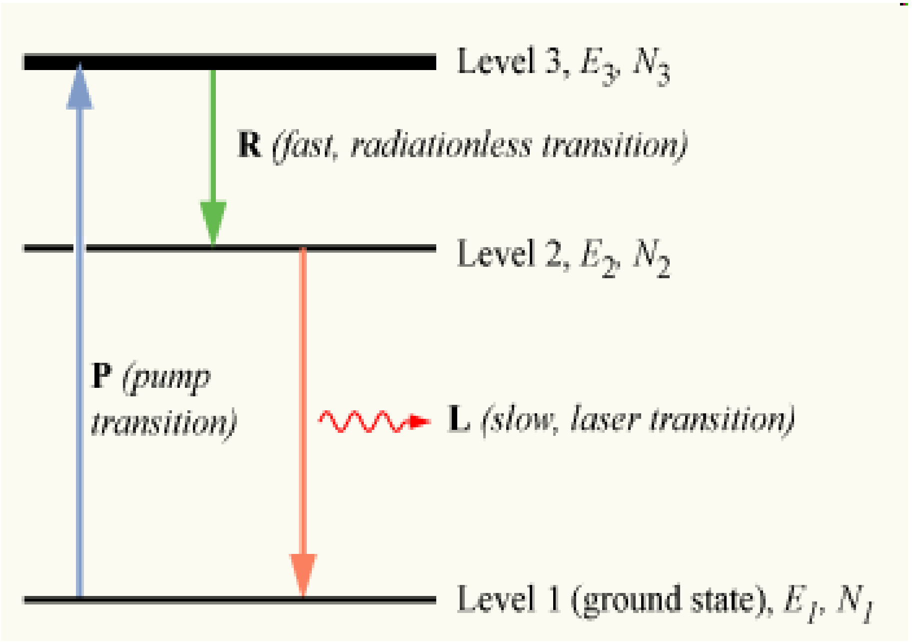
Laser medium need to have certain energy level structure to fulfil following functions:

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

Laser Medium

Energy levels can be:

- electronic system of individual atoms/ions/molecules in gas phase
- electronic system of atoms/ions/molecules as dopant in solid medium
- semiconductor electronic bands
- rotational-vibrational levels of molecules in the gas

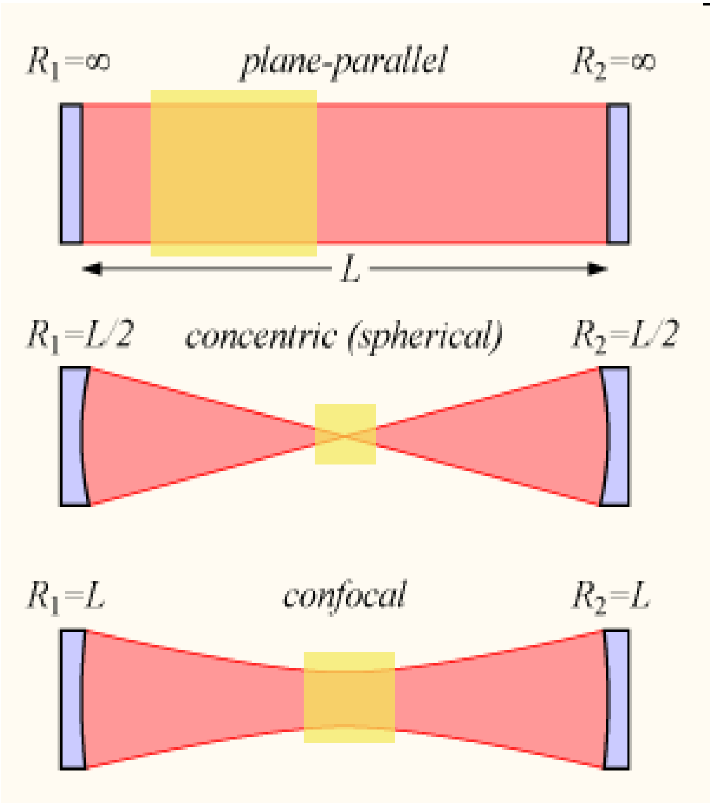


Resonator

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.

Pumping

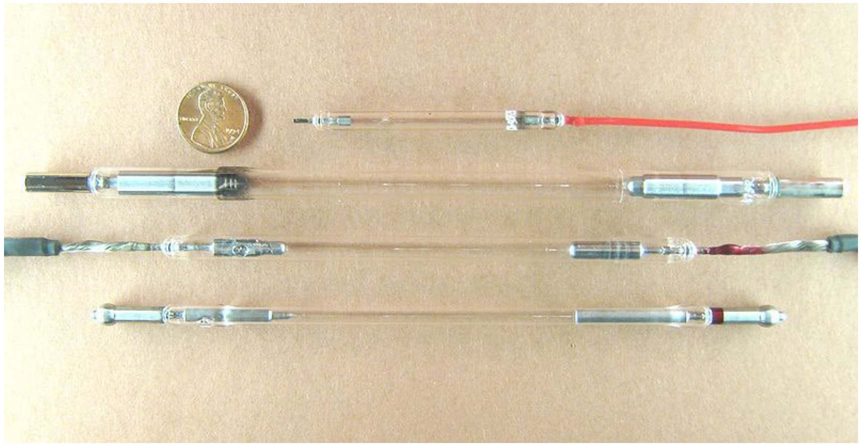
Pumping process must create population inversion in the laser medium

Energy can be provided through:

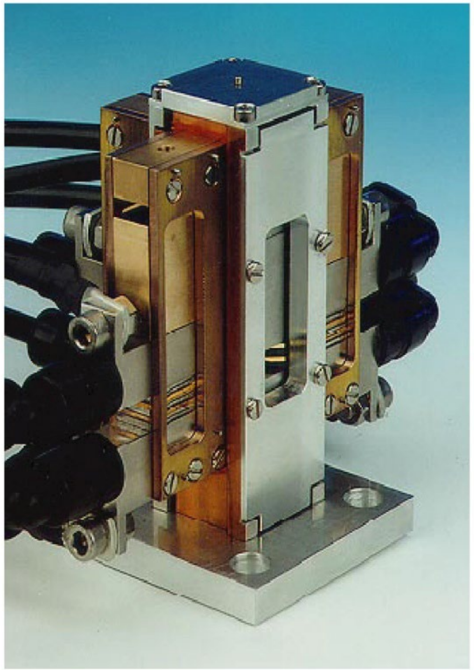
- optically – absorption of photons
- electrical current in semiconductor
- electrical discharge in gases
- some exotic methods:
  - gas dynamic pumping (adiabatic gas expansion)
  - chemical reaction (producing molecules in the excited state)
  - electron beam (for free electron laser)

Optical Pumping

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



T-Stack



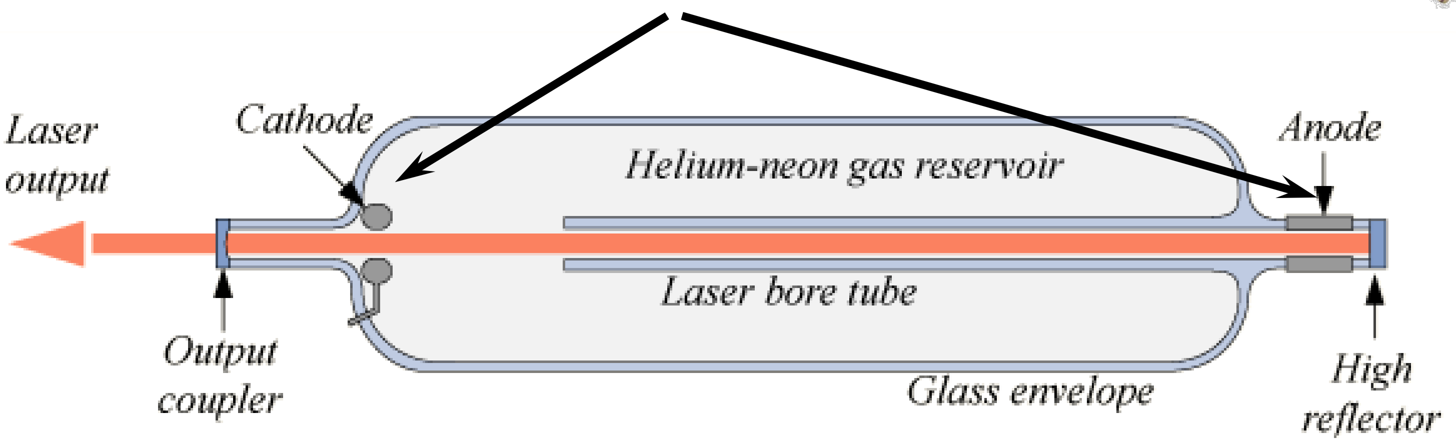
Electric Pumping

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

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

exciting by flowing current

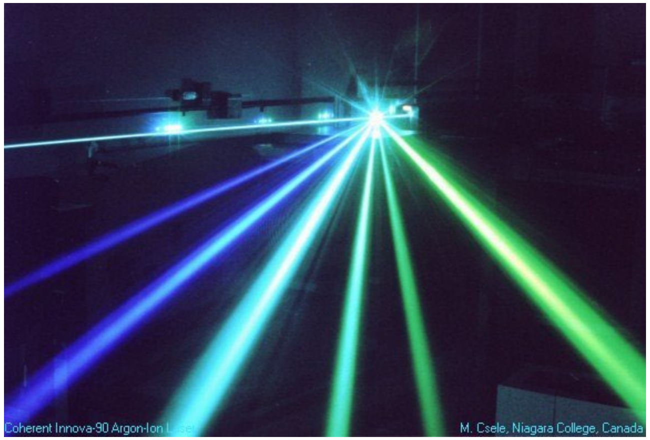
gas discharge take place between the electrods



Gas Lasers

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

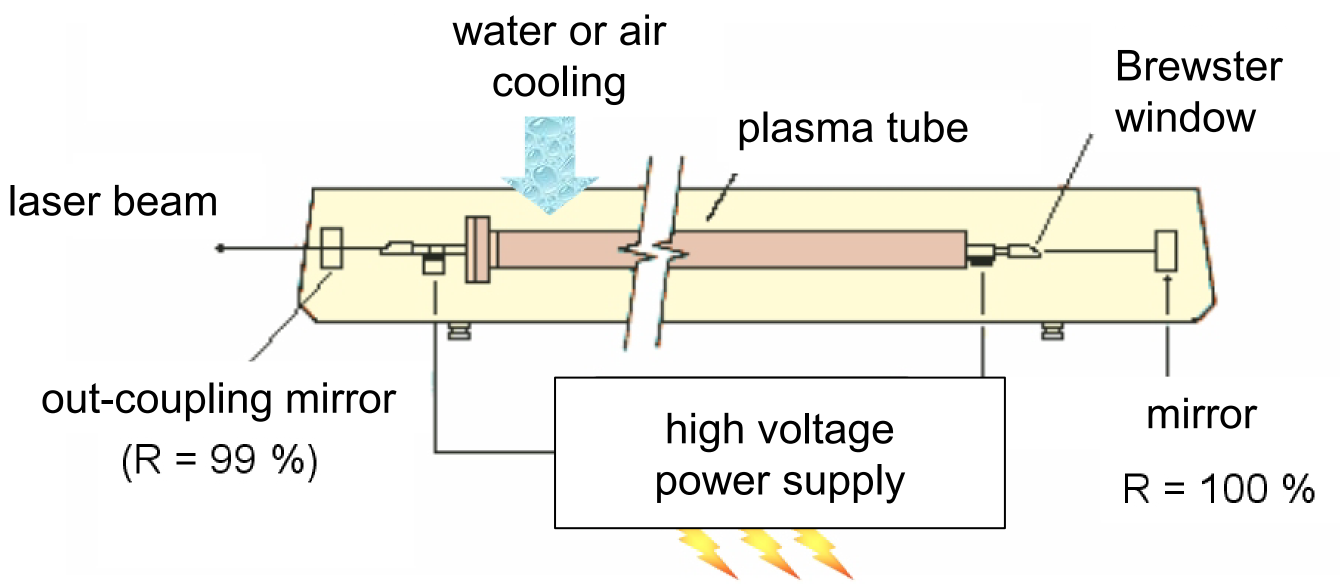
Argon



Argon + Krypton

Gas Lasers

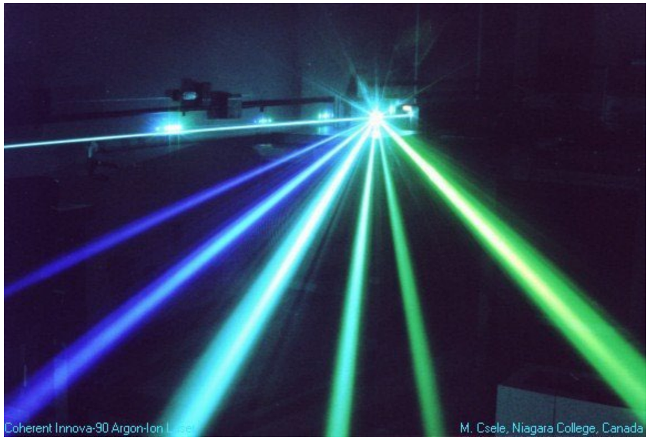
- Active medium = ionised gas (Ar, Kr...)
- Pumping = electrical discharge
- Resonator = usually plane parallel



Gas Lasers

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

Argon



Argon + Krypton

Content

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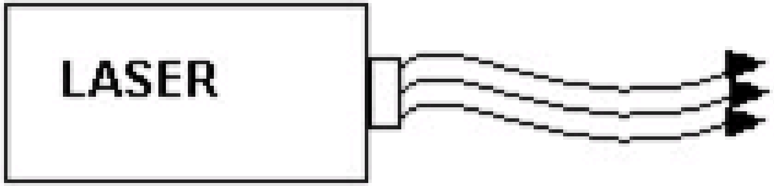
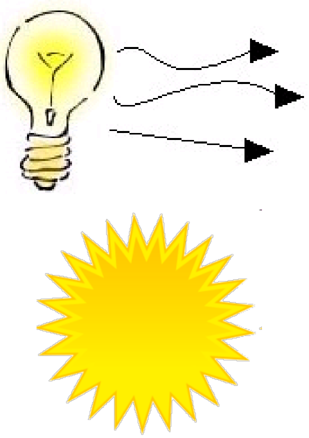
- Laser Types
- Pulsed Lasers

Propeties of Laser Radiation

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

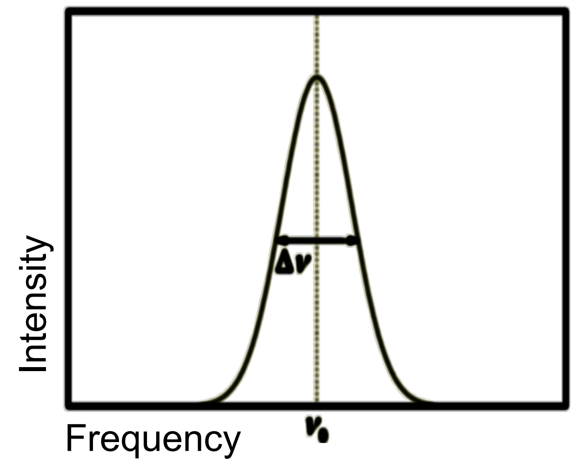




- multiple wavelength (colors)
- incoherent
- omnidirectional
- low brightness

Light Monochromaticity

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

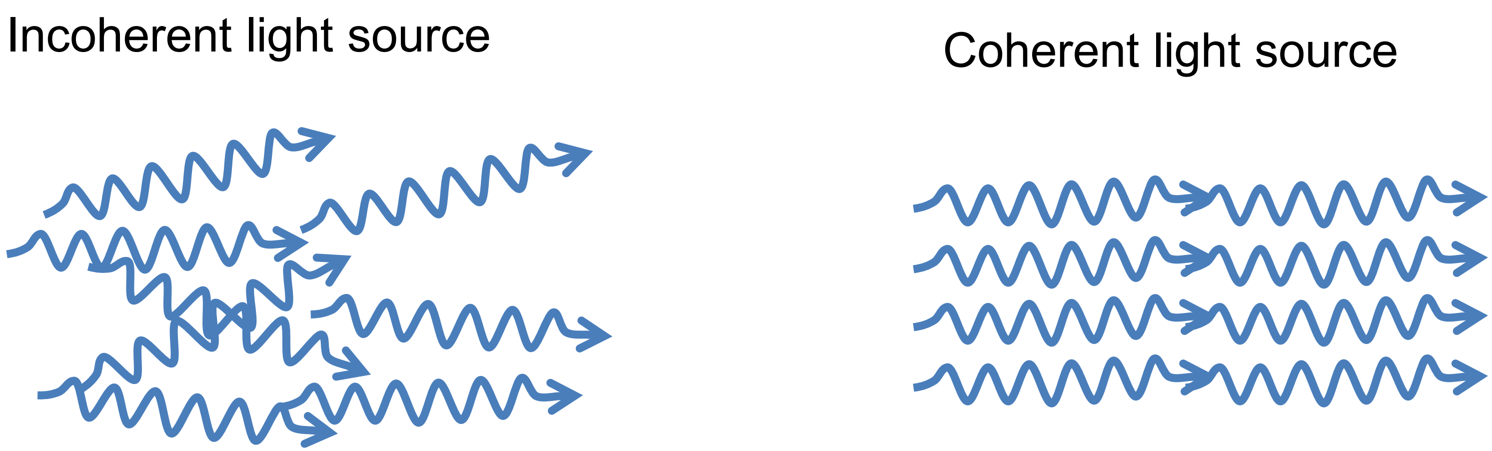


spectral line width ($\Delta\lambda$) of the laser depends on:

- 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



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)

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

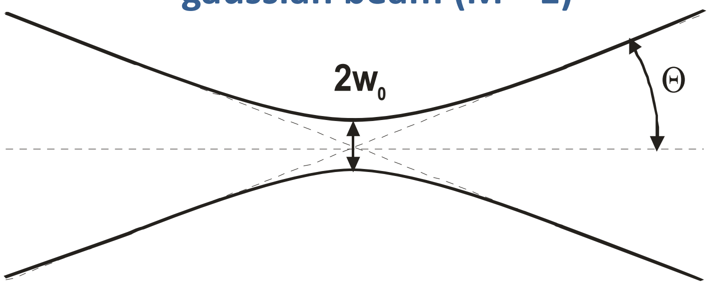
for non-ideal beam an M^2-factor is introduced

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

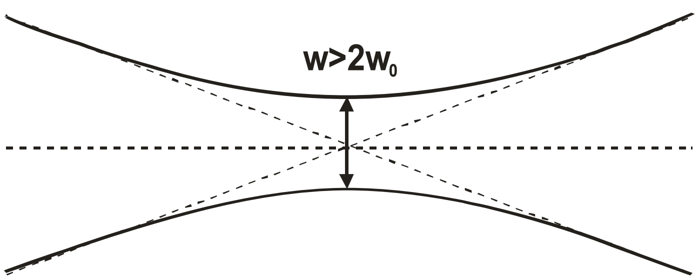
Radiance/Brightness is inversely related to beam quality

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

gaussian beam (M^2=1)



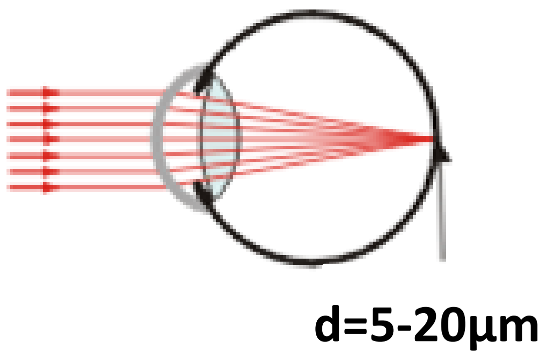
worse quality beam can not be focused as good with the same optics

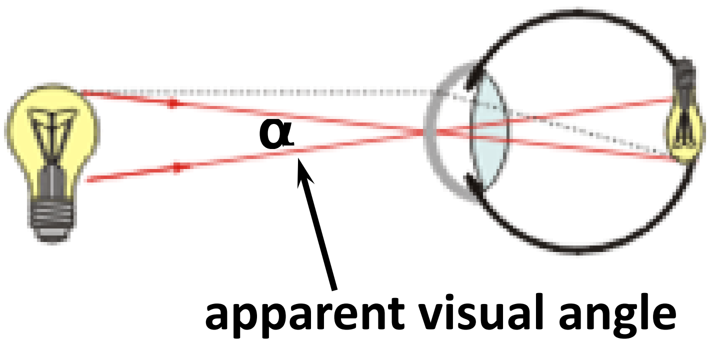


Laser vs. Conventional Light Sources

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:

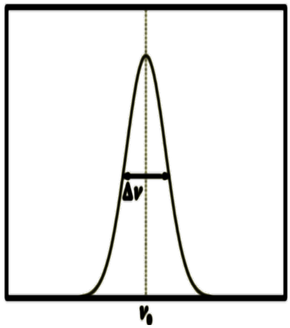
Sun	$\sim 1.5\times 10^{7}\dfrac{W}{sr\cdot m^{2}}$
1 mW laser	$\sim 3\times 10^{9}\dfrac{W}{sr\cdot m^{2}}$
1 W laser	$\sim 3\times 10^{12}\dfrac{W}{sr\cdot m^{2}}$

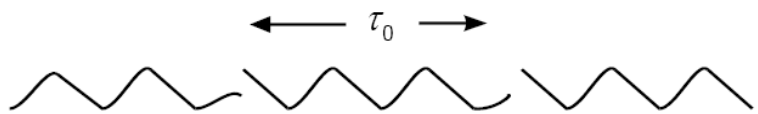
Irradiance on the eye retina is proportional to the radiance (brightness) of the source:

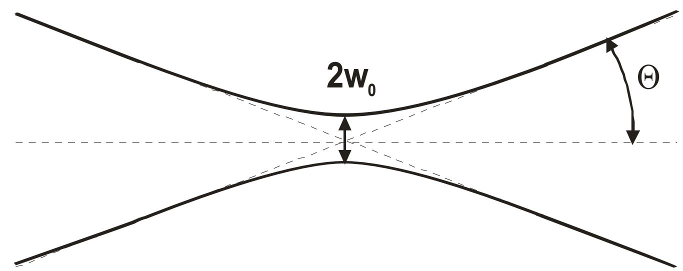
- 1 mW laser already gives 100 times (two orders of magnitude!) higher power density (W/m^2) than staring in the sun.
- 1 W laser - 100 000 times (five orders!) higher power density

Propeties of Laser Radiation

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







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

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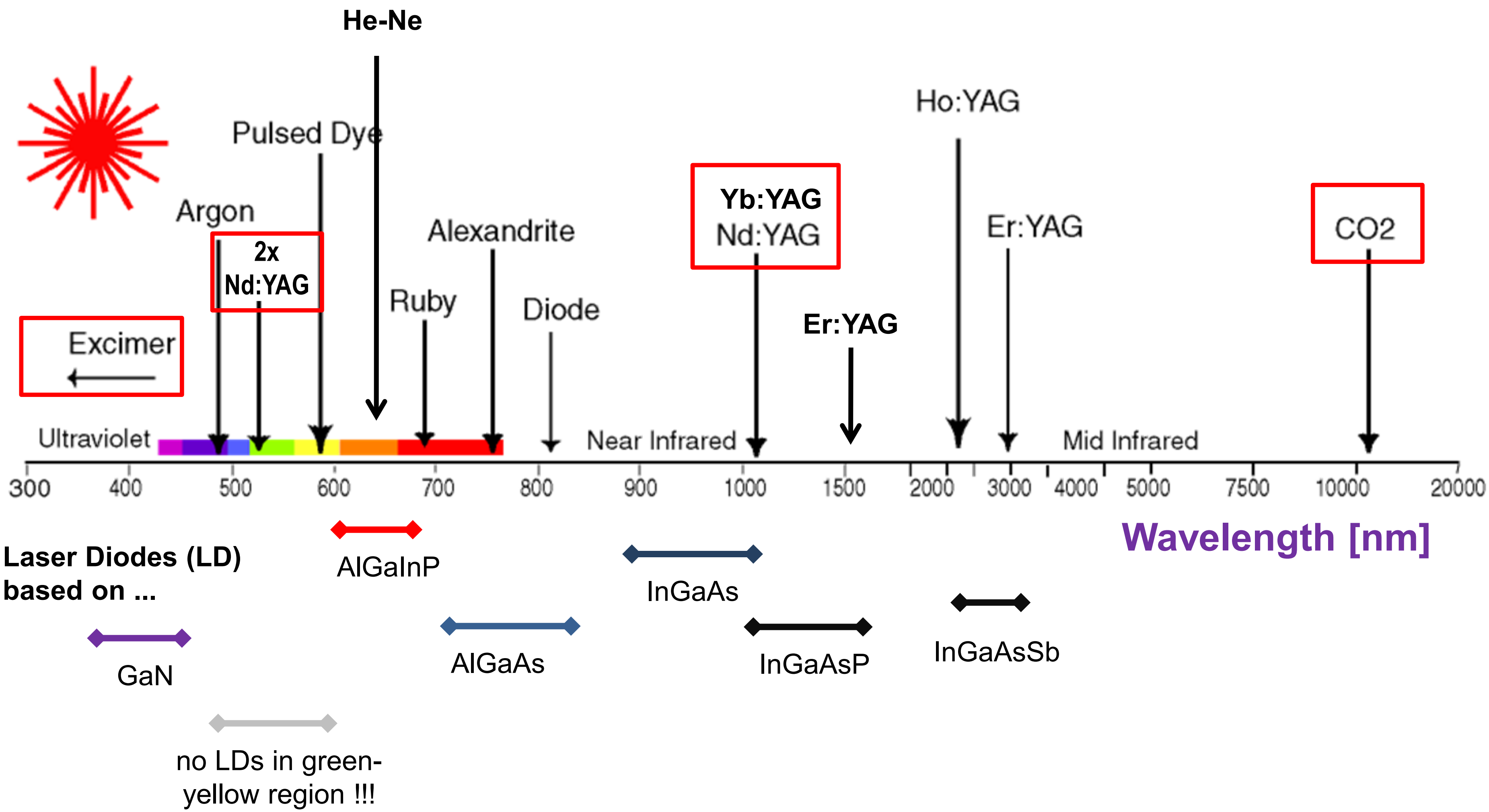
Laser Types: wavelength

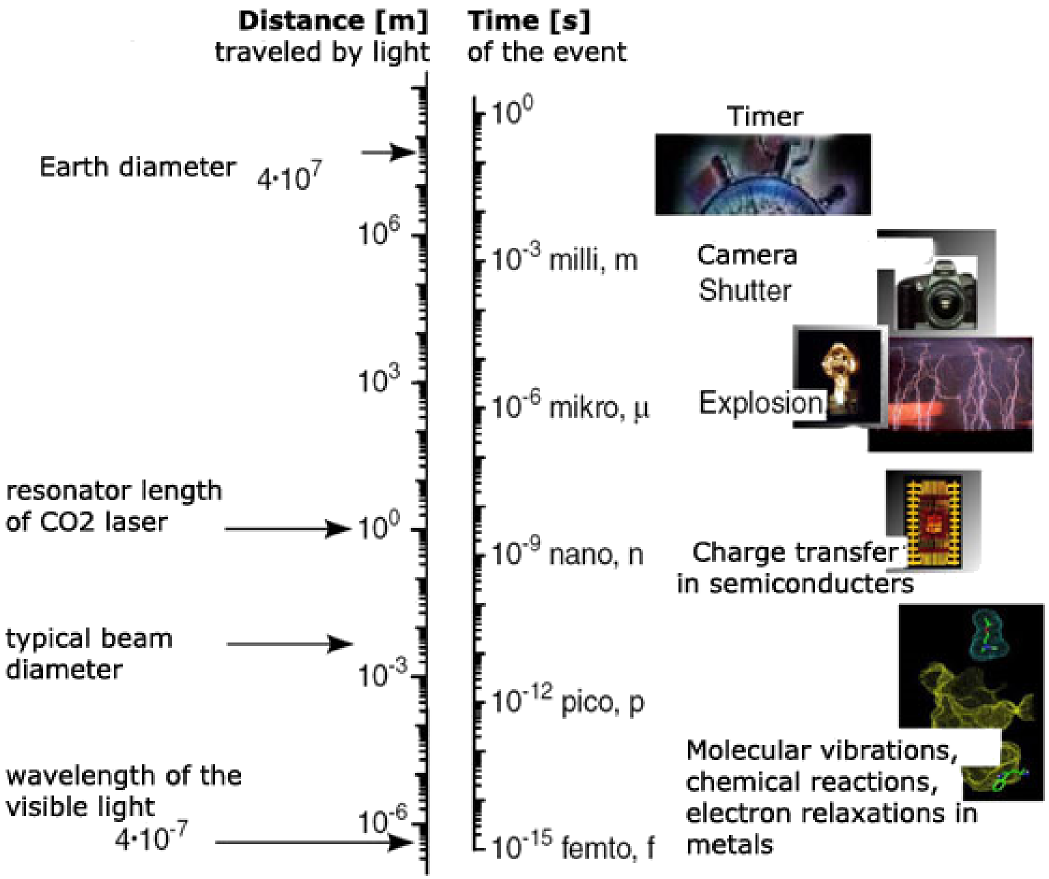


used for laser processing

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

Content

Time Scales



Pulse length of the laser determined by:

Pump power modulation ~0.1ms

rotating mirror, shutter

relaxation oscillations

passive Q-switch (>1ns)

Pockel cell,
active mode-locking (1>ps)
passive mode-locking
electro-optical, acousto-optical modulators (>2 fs)

Pulse compression
and dispertion compensation

Themal processes

Heat diffusion

Thermalization crystalline lattice – electrons

Light absorption by electrons

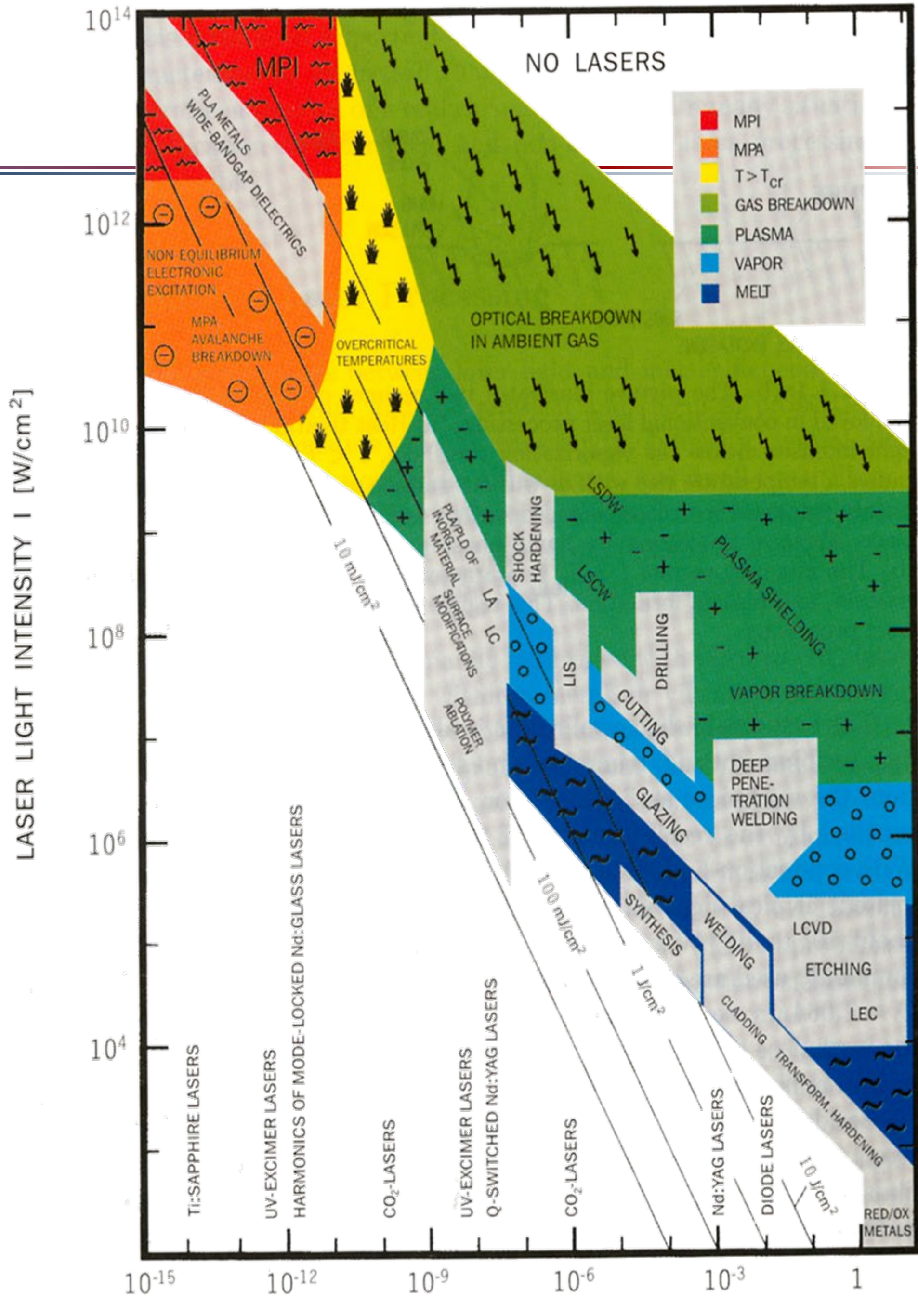
Laser Types: Pulsed & CW

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

Laser Types: Pulsed & CW

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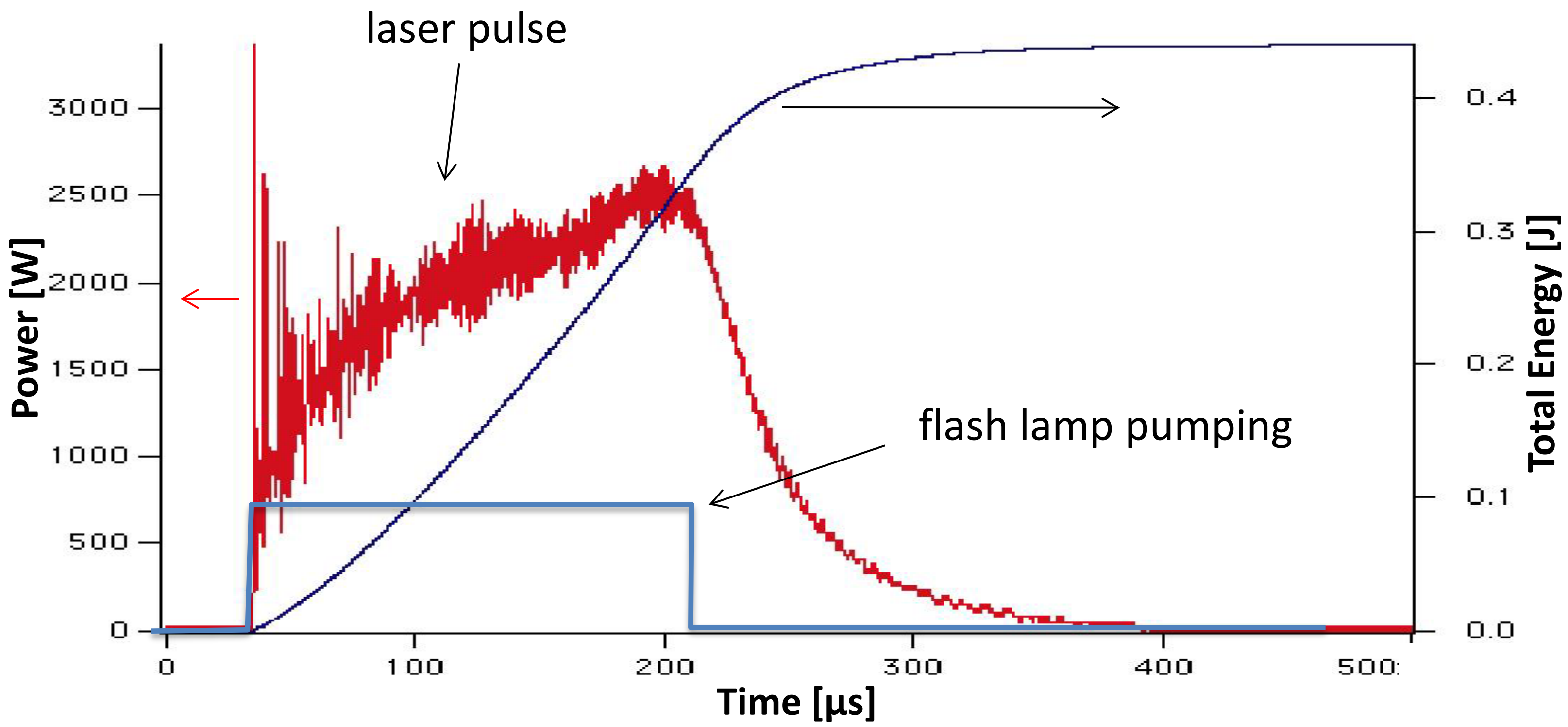
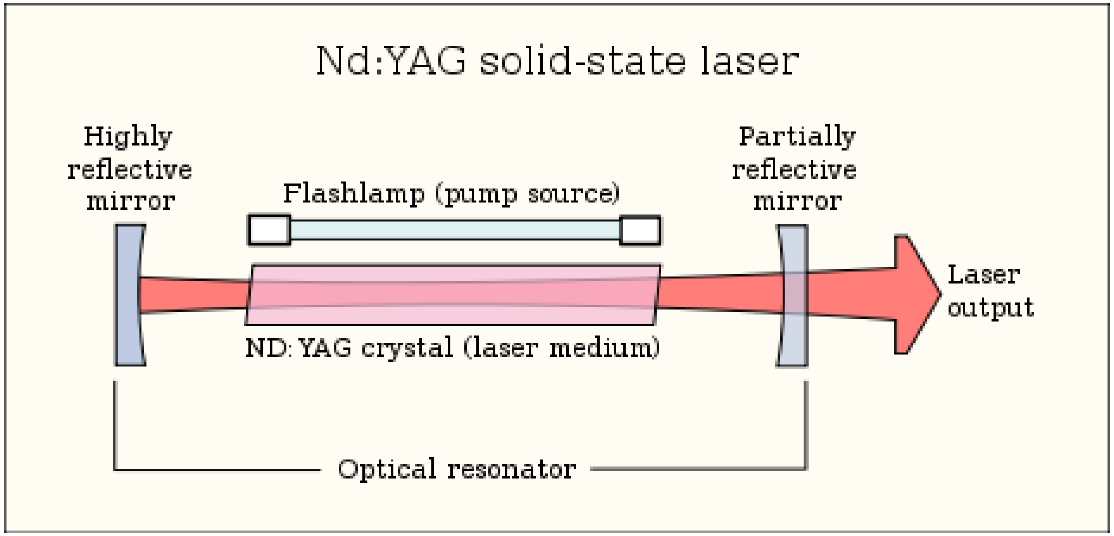
Free-running Lasers

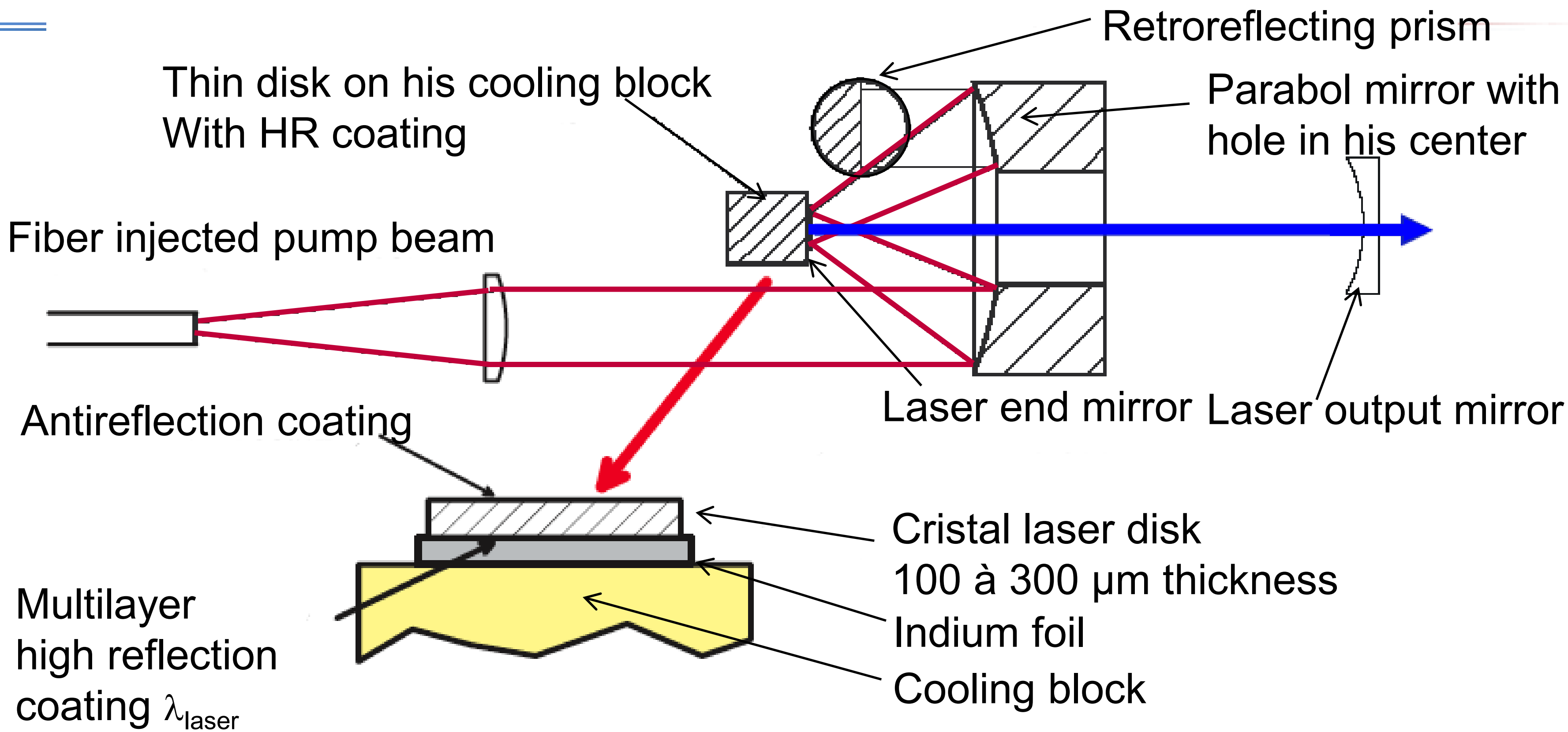


- „Free-running“ = no special pulse duration regulation
- pulse duration determined by pump duration, typically 10 µs – 1 ms
- peak power is relatively low
- total pulse energy can be quite high

Nd:YAG Laser- Flash Lamp Pumped



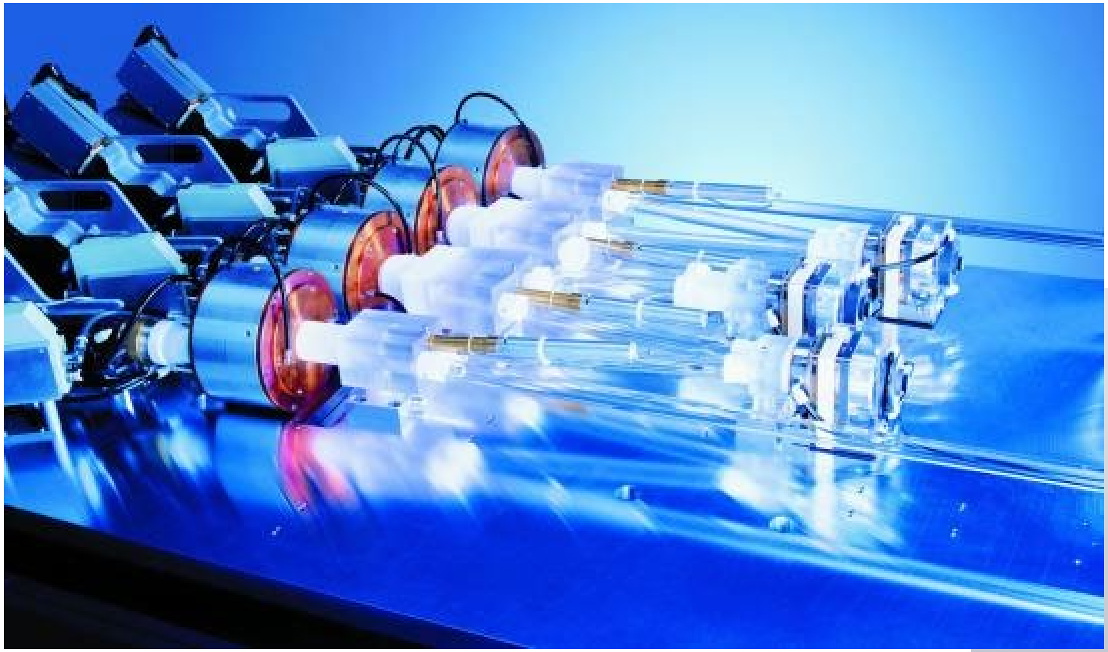
Yb:YAG Thin Disc Laser



Avantages:

High power
High beam quality
Very efficient cooling and longitudinal thermal gradient only.

Thin Disk Laser



four laser head combined give 8kW optical power at 1030 nm (IR)

TRUMPF

Fiber Lasers

Single mode

Multimode

(Courtesy of IPG Photonics Corp.   Bill Shiner)

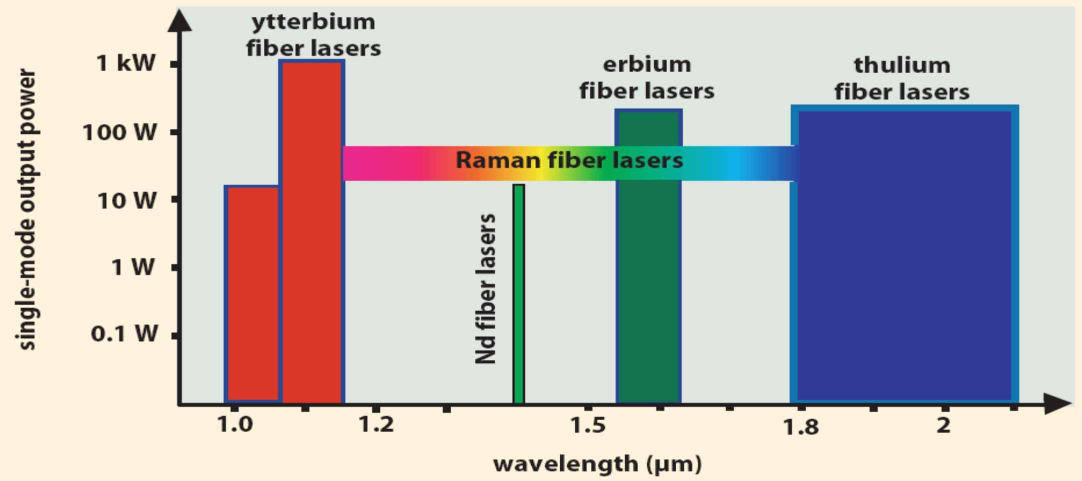


Figure 2. *Wavelengths available with single-mode fiber lasers.*

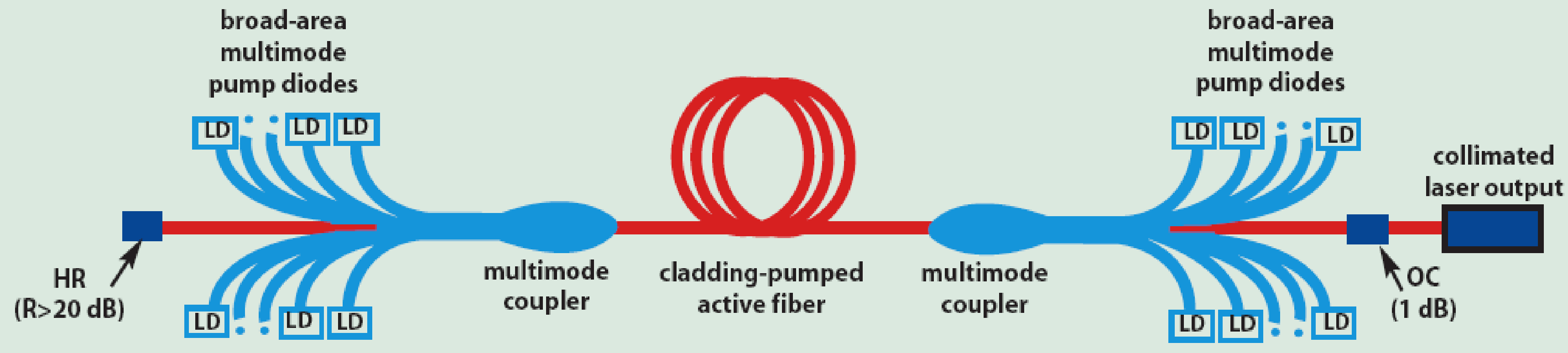


Figure 1. *Schematic of a typical single-mode fiber laser utilizing single-emitter diodes.*

Fiber Lasers

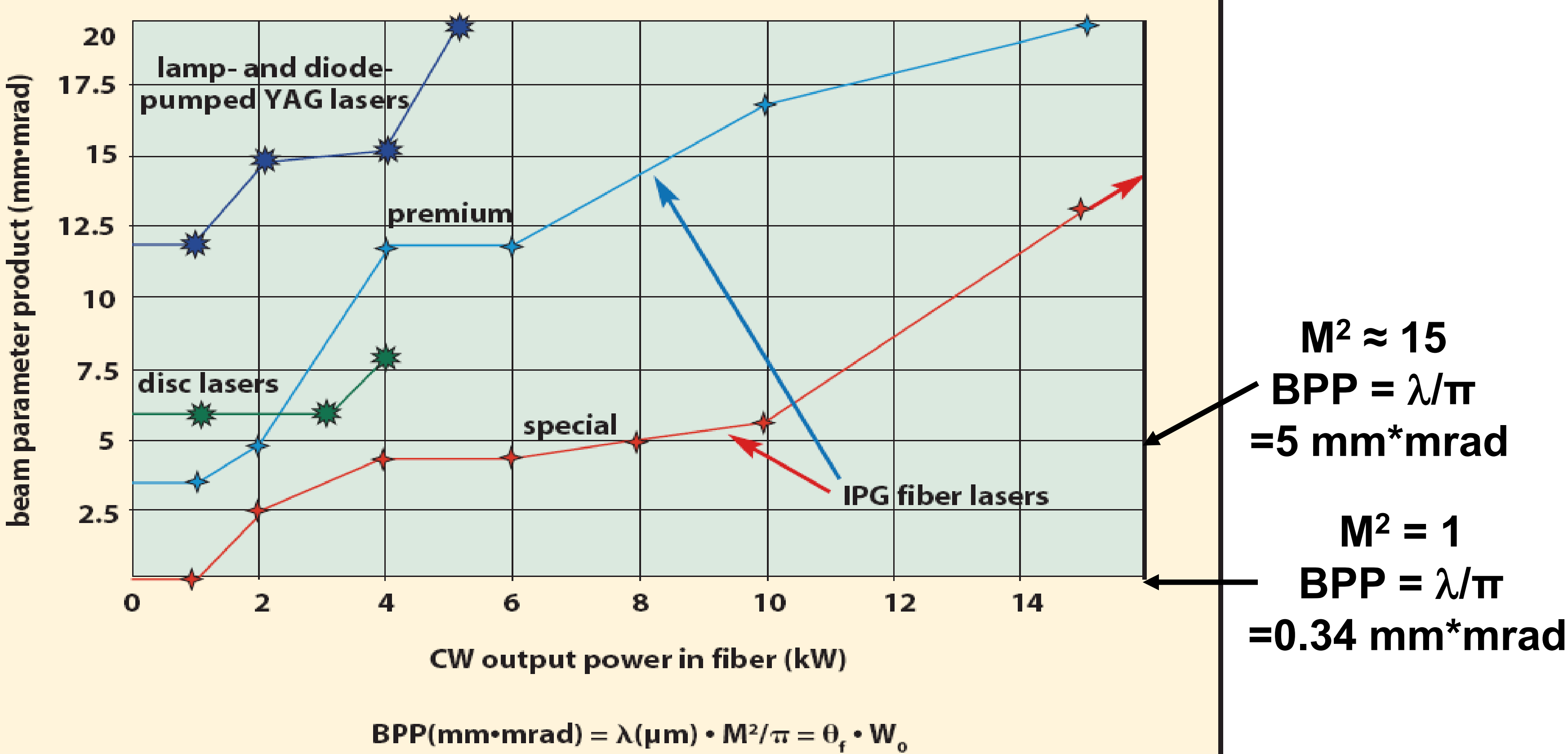
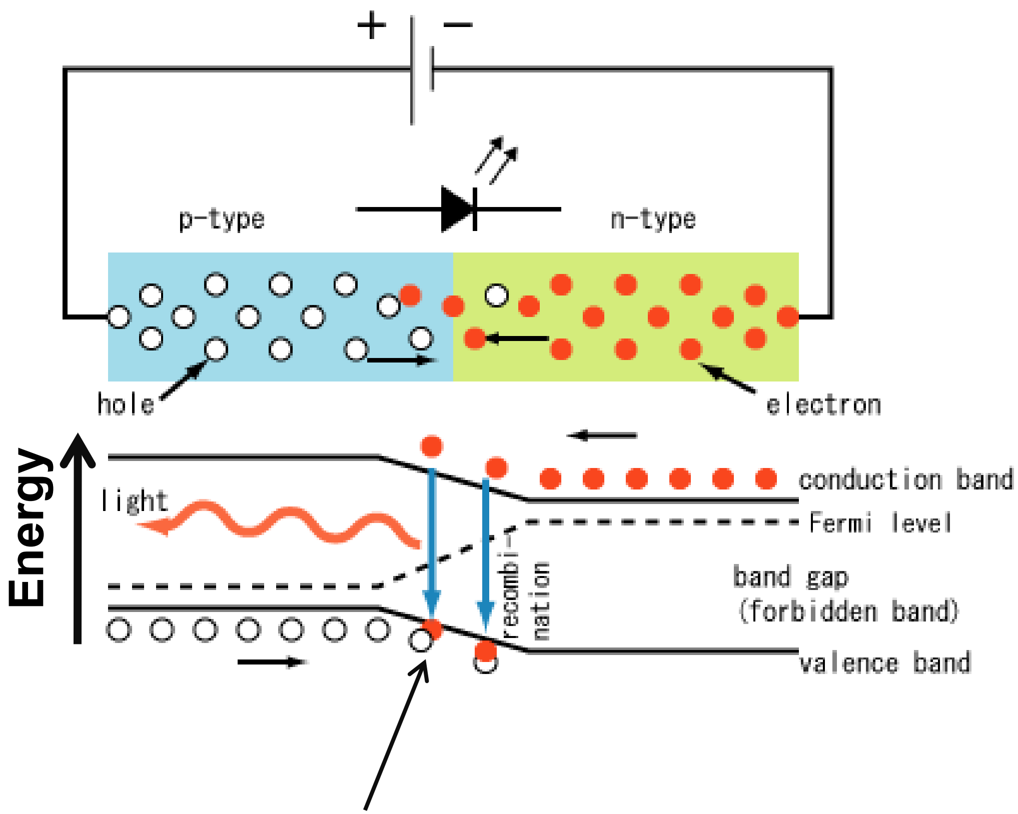


Figure 3. *Beam quality of kilowatt-class fiber lasers.*

(Courtesy of IPG Photonics Corp)

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

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

Q-switch mode

Idea of Q-switch regime – accumulate energy and release in a short time

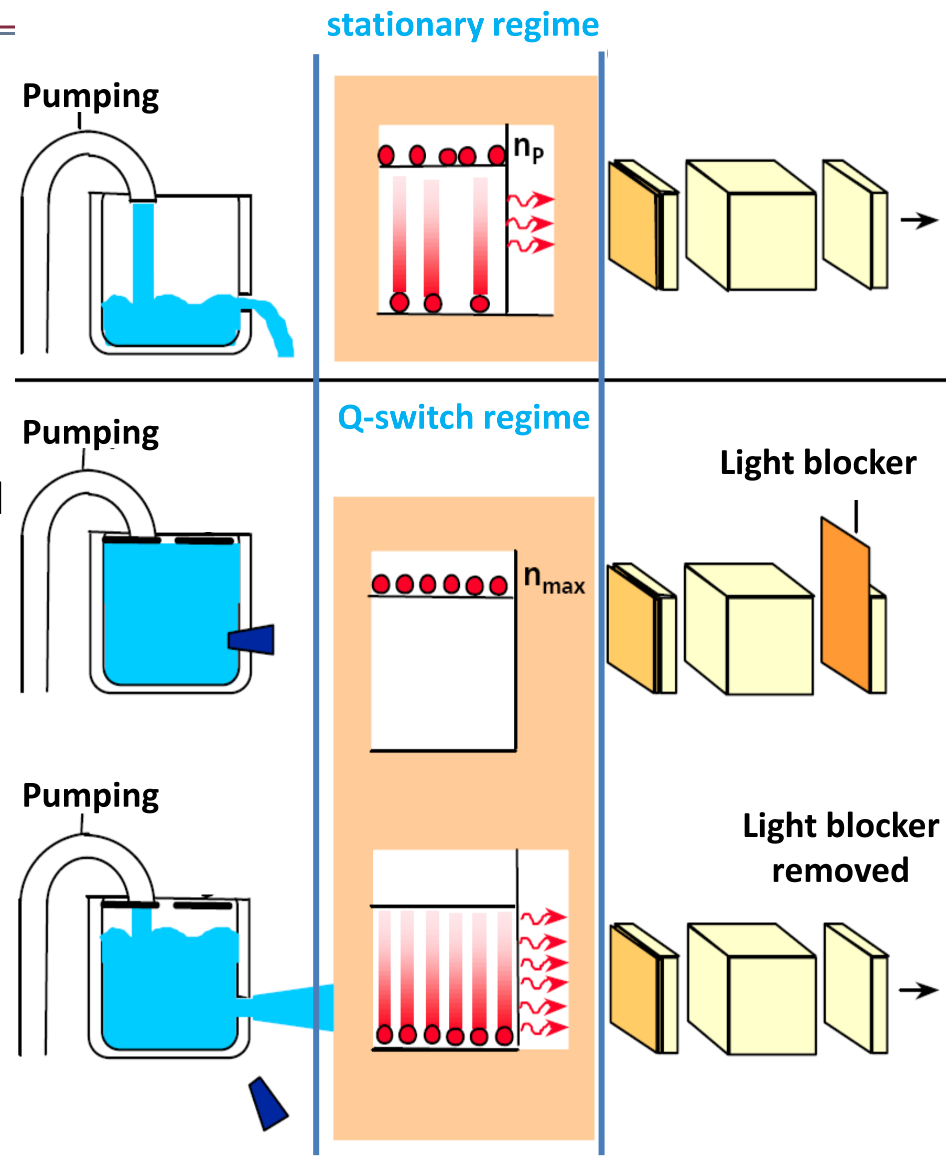
Q → stands for quality of resonator, quality is switched in time

Resonator state A – resonator is closed/blocked

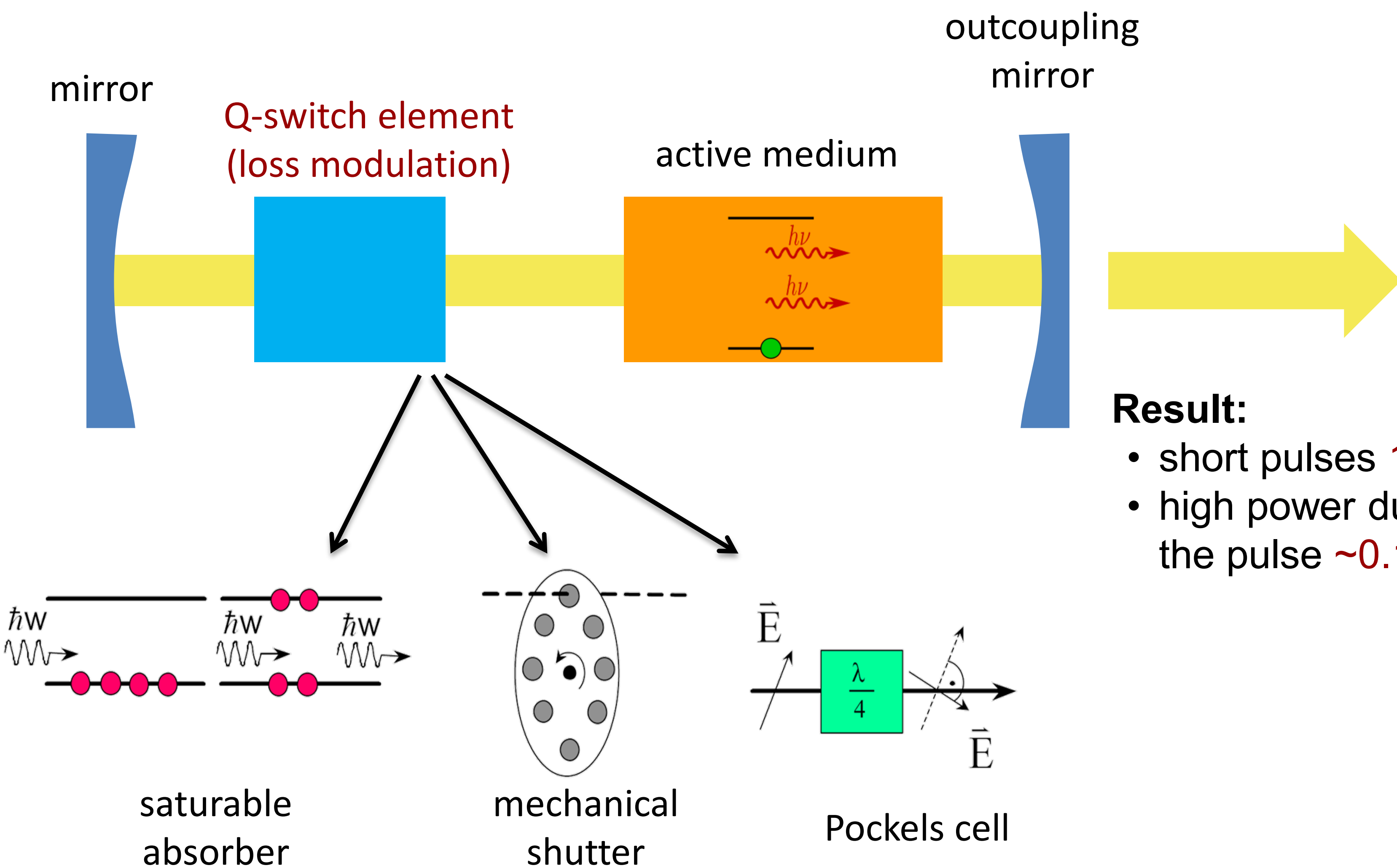
- stimulated emission is not possible
- energy is accumulated

Resonator state B – resonator opens abruptly

- inversion is high → amplification coefficient is very high
- all accumulated energy is emitted in a short burst/pulse



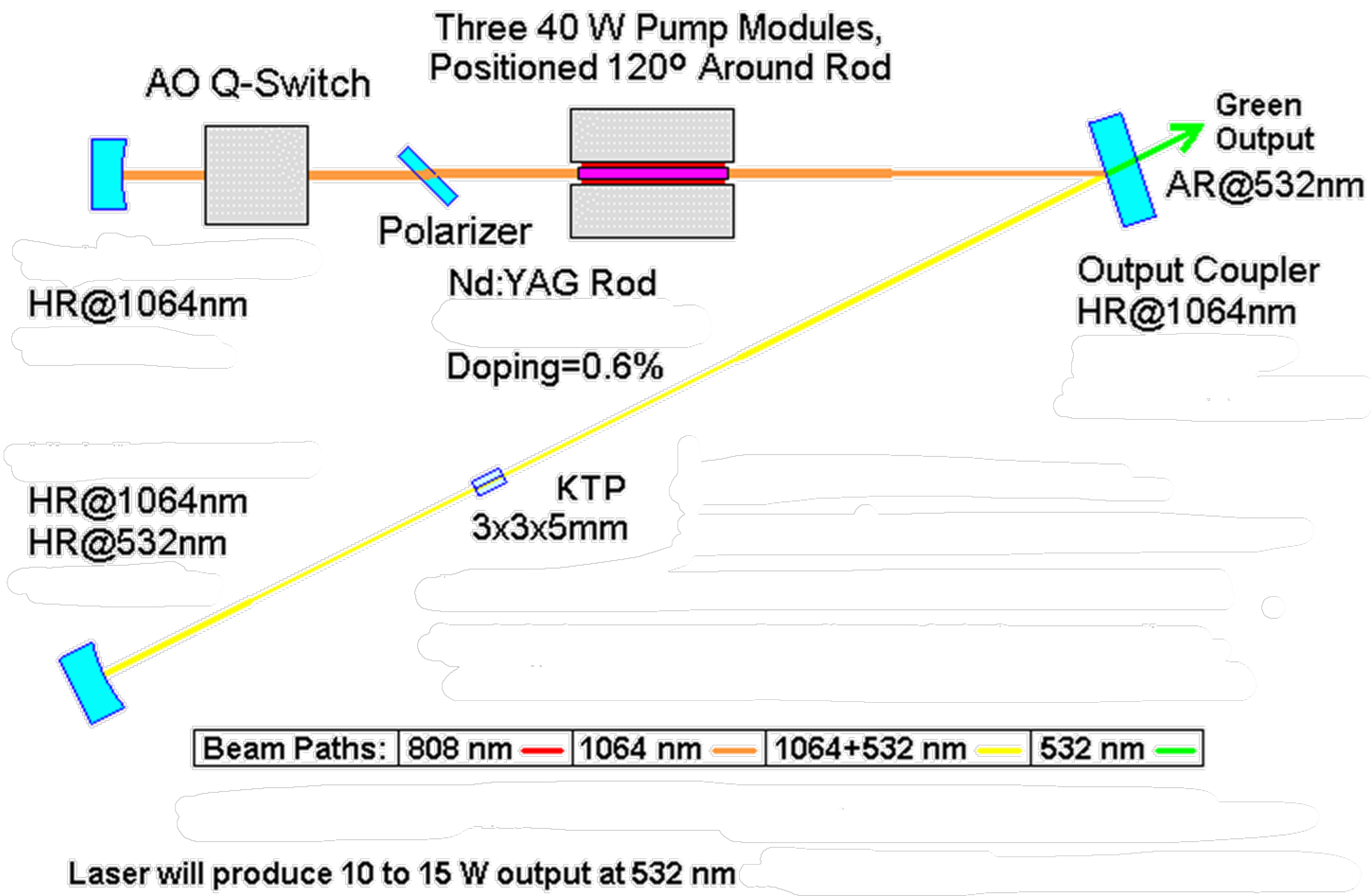
Q-switching the Resonator



Result:

- short pulses 1-100 ns
- high power during the pulse ~0.1-100 MW

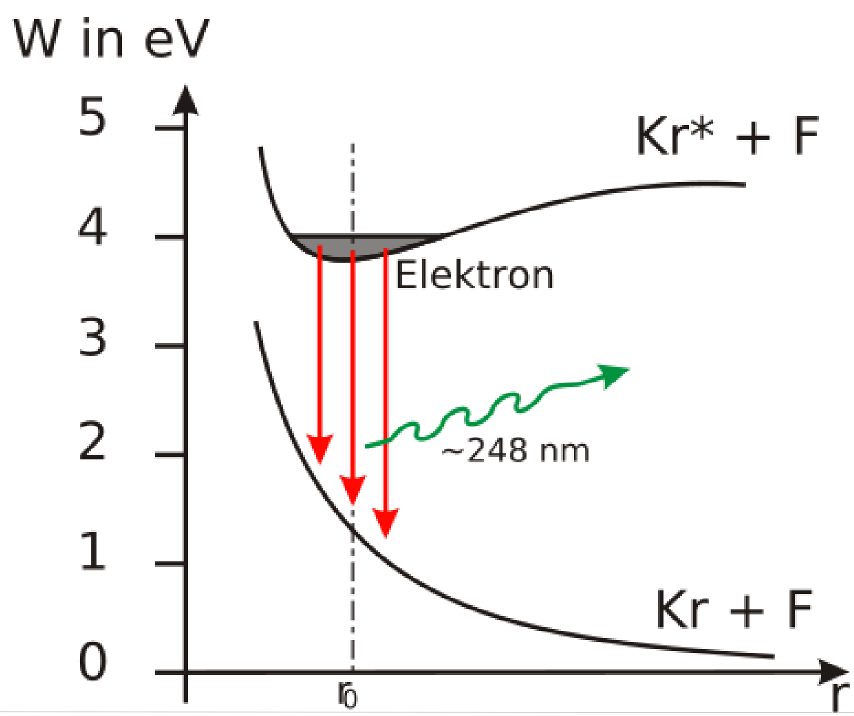
Q-swiched Solid State Lasers

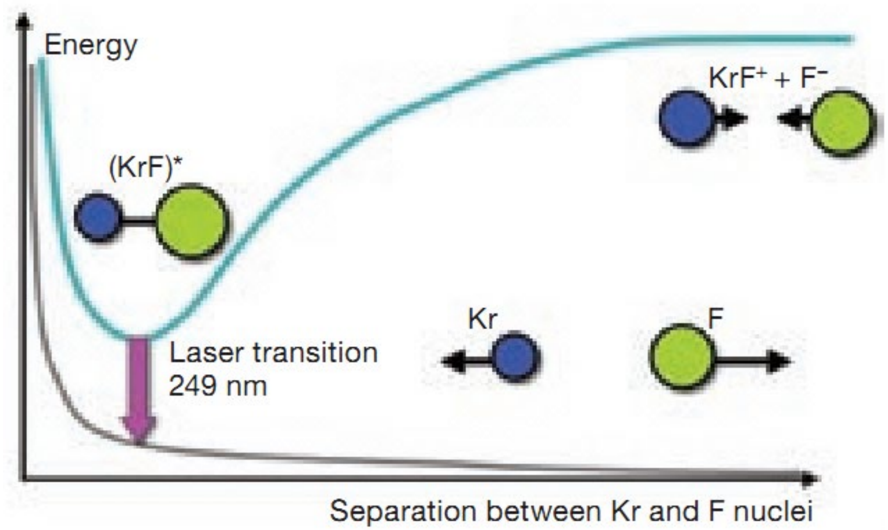


Typical High Power Green DPSS Laser Optical Path

What is an Excimer laser?

- Gas laser using a combination of a noble and a reactive gas
- Under pressure and electrical stimulation a pseudo molecule called Excimer (= excited dimer) is created
- By spontaneous or stimulated emission it dissociates back into two unbound atoms (laser with one energy level!)





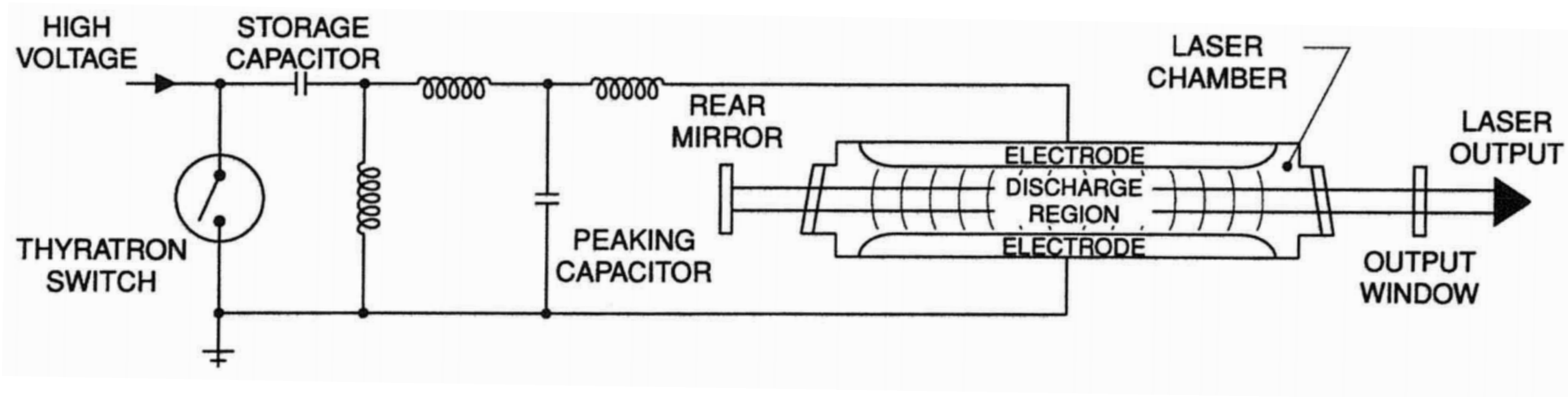
Wavelength of Excimer Lasers

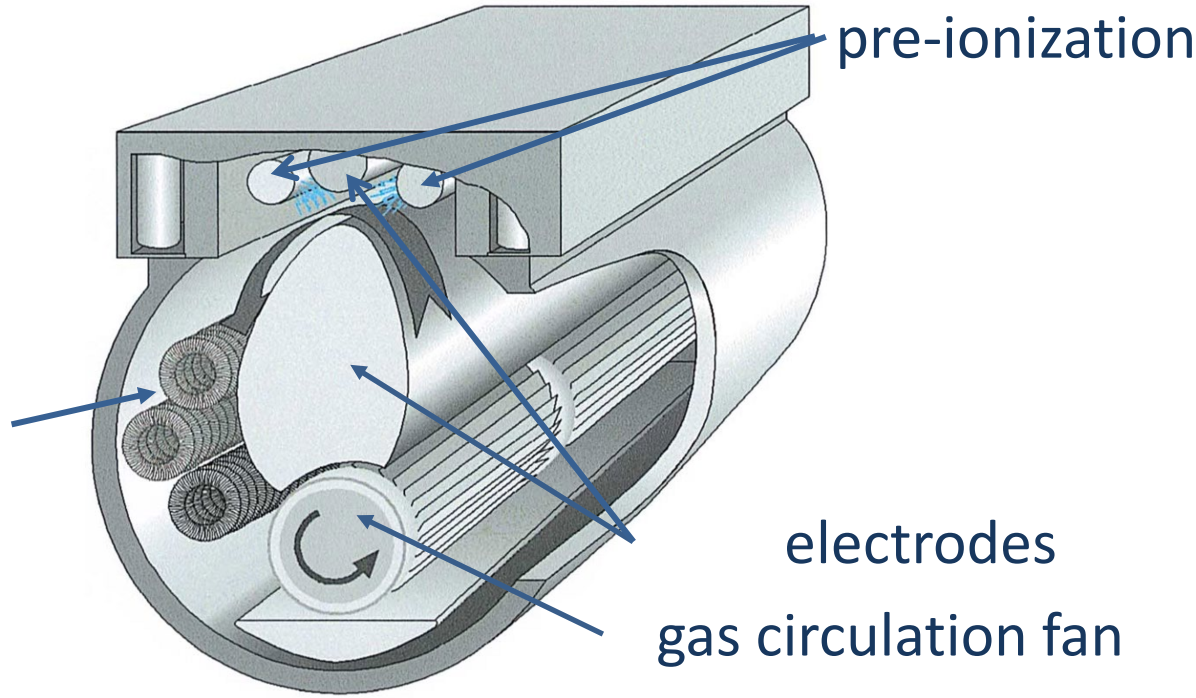
- The wavelength of an excimer laser depends on the molecules used (can not be tuned)
- emission is in the ultraviolet range

Excimer	Wavelength
F_2 (fluorine)	157 nm
ArF (argon fluoride)	193 nm
KrF (krypton fluoride)	248 nm
XeBr (xenon bromide)	282 nm
XeCl (xenon chloride)	308 nm
XeF (xenon fluoride)	351 nm

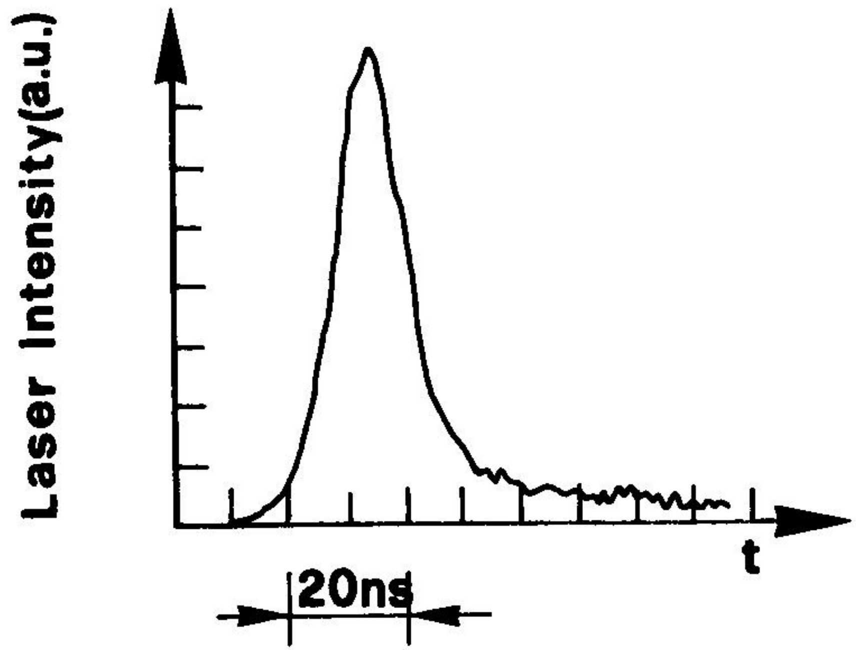
Most important technologically are **ArF (193 nm)** and **KrF (248 nm)**

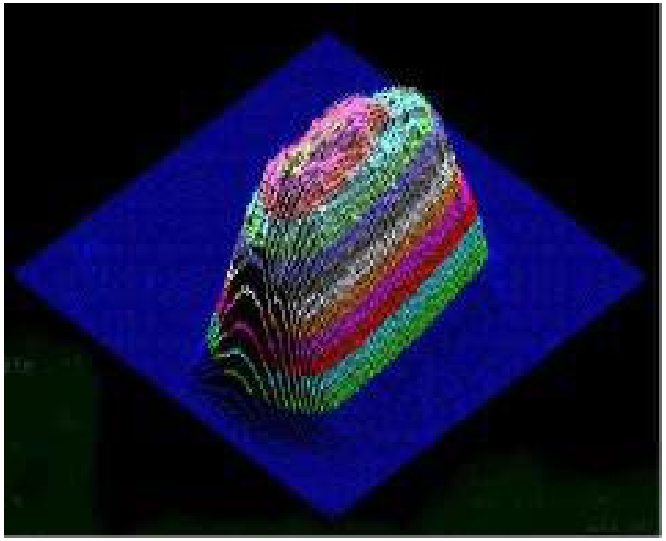
Schematic Set-up

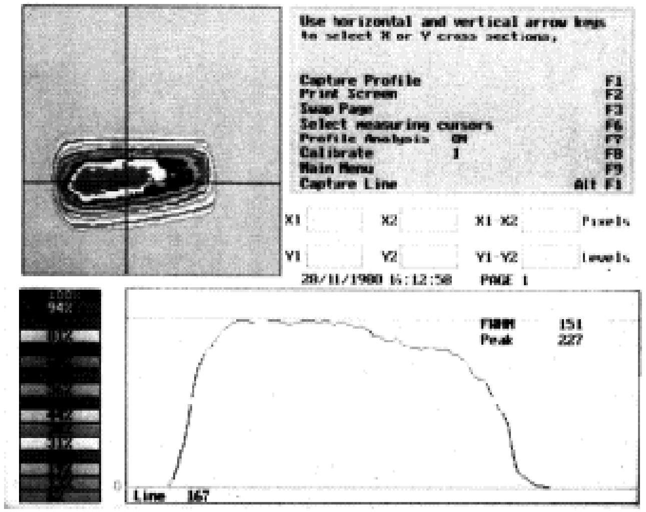




Temporal and Spatial Profile of the Beam







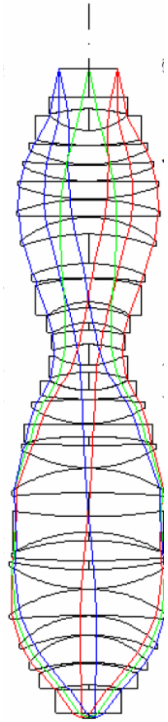
- ~20 ns is a characteristic pulse length of ArF and KrF lasers
- determined by the excimer molecule properties - can not be easily tuned

Excimer laser technical specs

- Average power: 1 W – 1000 W
- Peak power: up to 50 MW
- Pulse frequency: 1 Hz – 6 kHz
- Pulse duration: 5ns – 200ns

Microelectronic production

State-of-the-art microstepper with laser and lens



Wavelength 193 nm

Lens		Field Size	Overlay	Throughput
NA	Resolution	X & Y	16-point Alignment	300 mm Wafers 30 mJ/cm2 (125 shots)
Variable 0.85-1.35	38 nm	26 X 33 mm	2.5 nm*	175 wph

* Single machine overlay including chuck dedication

$NA = 0.85\ y_{imax} = 13.8mm,\ \lambda = 193nm$ (ArF) J

Research High Power Excimer Laser

Courtesy of John Sethian and F. Hegeler

The ELECTRA KrF laser at NRL (Naval Research Laboratory)

- pulses of 250 to 700 J at repetition rates of 1-5 Hz
- electron beam pumped

History of excimer lasers has started at NRL around 1975 with emission from XeBr

Laser Types: Pulsed & CW

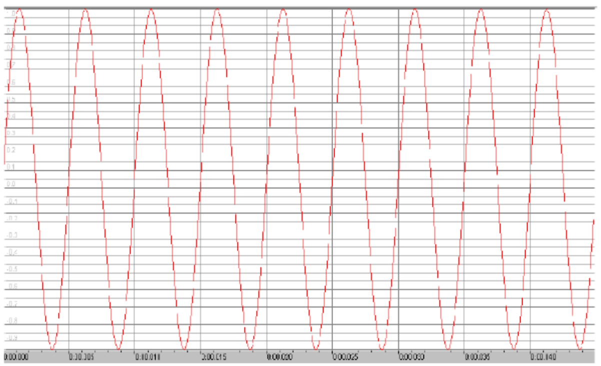
Type of laser	Pulse length determined by	Typical pulse length	Characteristic pulse peak power
Continuous wave (cw)	-	∞	Ws – kWs
Free running laser	Pump pulse length (flash lamp)	100 µs – 1ms	kWs
Q-switched laser	Time constants of active material and modulating element	1 ns – 100 ns	MWs
Mode-locked laser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

Why do you want very short pulses?

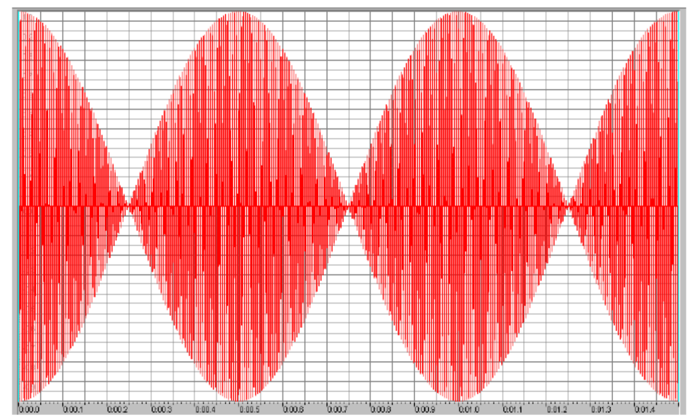
Mode-locking regime

Mode-locked pulses – result of inteference of many „locked“ (phase/frequency related) light waves

interference of waves with two different frequencies



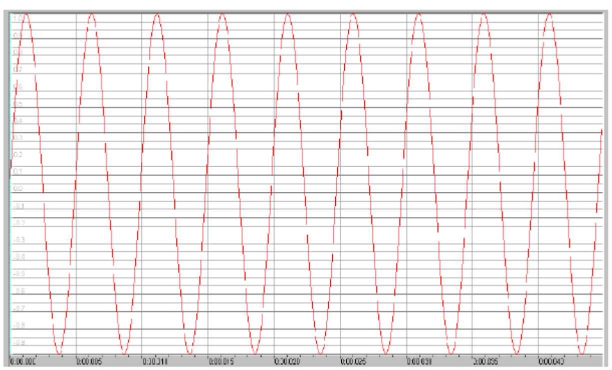
$$A_{S2}(t) = A_1(t) + A_2(t) = \sin(2\pi\nu_1 t) + \sin(2\pi\nu_2 t)$$



200 Hz

t [s]

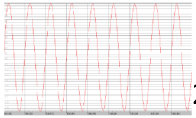
202 Hz

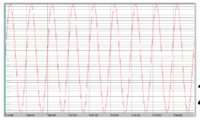


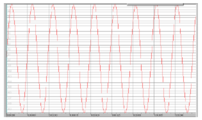
t [s]

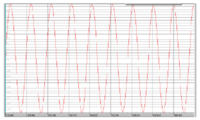
Mode-locking regime

interference of waves
with four equidistant frequencies

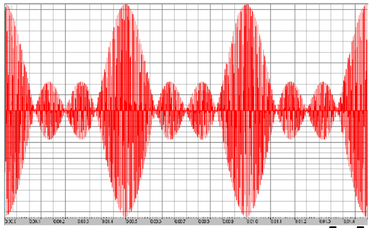

200 Hz


202 Hz


204 Hz


206 Hz

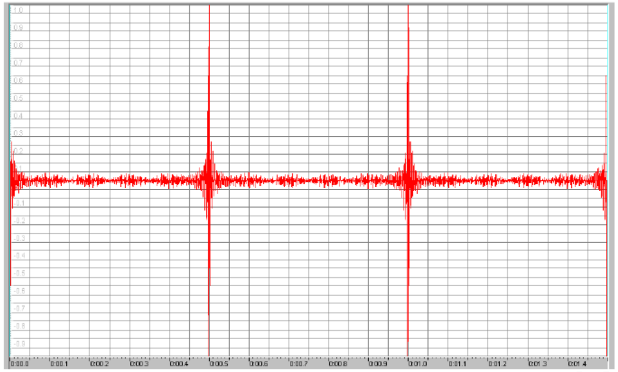
$A_{S4}(t) = A_1(t) + A_2(t) + A_3(t) + A_4(t)$
$= \sin(2\pi\nu_1 t) + \sin(2\pi\nu_2 t) + \sin(2\pi\nu_3 t) + \sin(2\pi\nu$



interference of waves
with 120 equidistant frequencies

$$A_{S120}(t) = \sum_{n=0}^{120} \sin[2\pi(\nu_1 + n\Delta\nu)t]$$

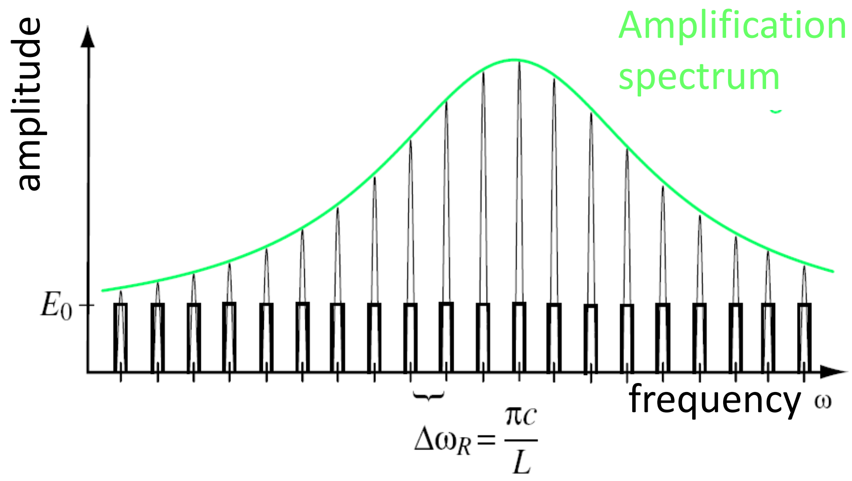
ν_1 = 200 Hz
$\Delta\nu$ = 2 Hz



Mode-Locking

- Different interfering light waves are longitudinal modes of the resonator
- more modes → shorter the pulse

- Typical mode-locked lasers have:
  ultra short pulses ~ 50 fs – 1 ps
  very high peak power ~ 1MW - 10 GW



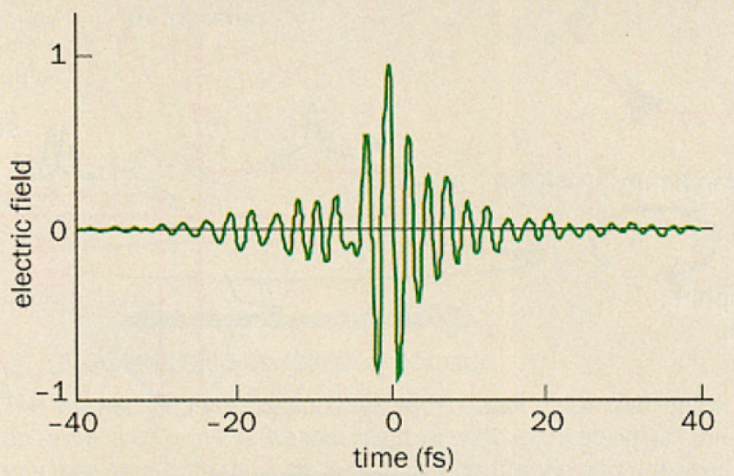
Heisenberg uncertainty principle: $\Delta\nu \cdot \Delta\tau \geq 1$

⇒ very short light pulses cannot be very monochromatic ⇒ special active media with broad emisssion spectrum needed for very short (femtosecond) pulses

Ti:Sapphire is typical active medium for fs-lasers

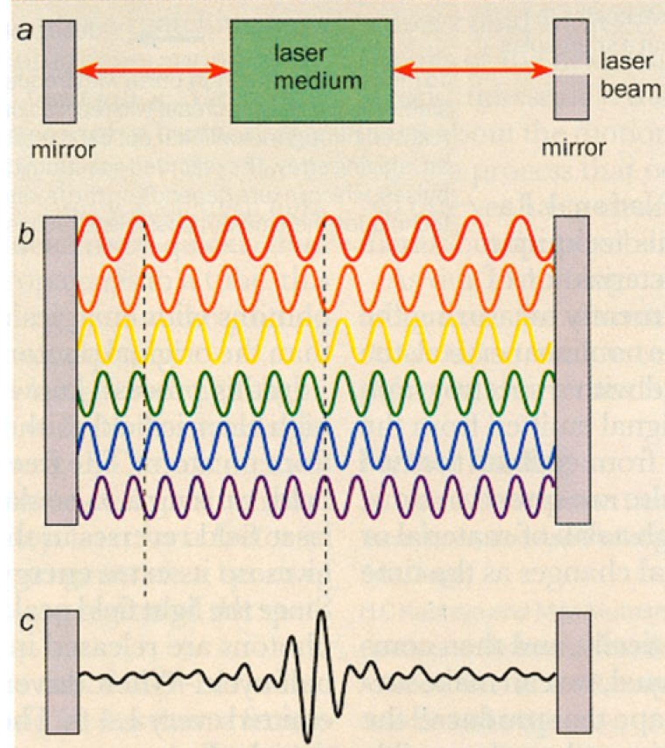
Examples of Ultra-short pulses

2 Short light pulses



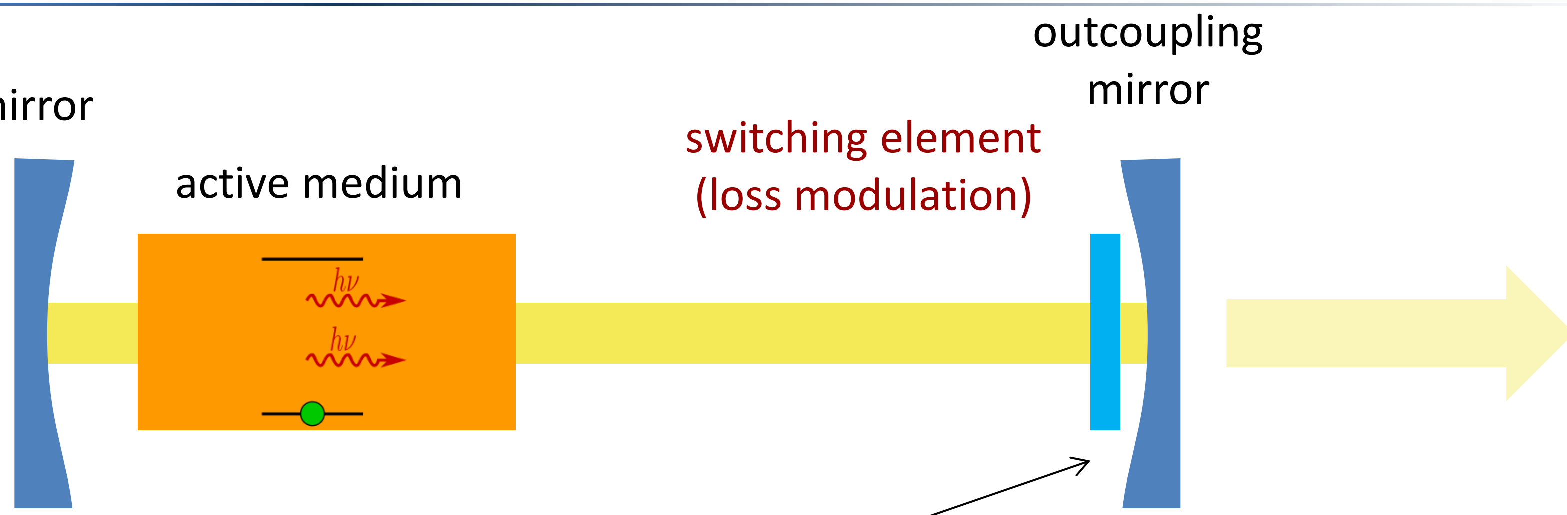
Maxim Pshenichnikov of the University of Groningen in the Netherlands has measured the electric field of a 5 fs light pulse, the shortest complete pulse measurement made to date. The output pulse consists of the two complete cycles centred around 0 fs.

3 Laser modes



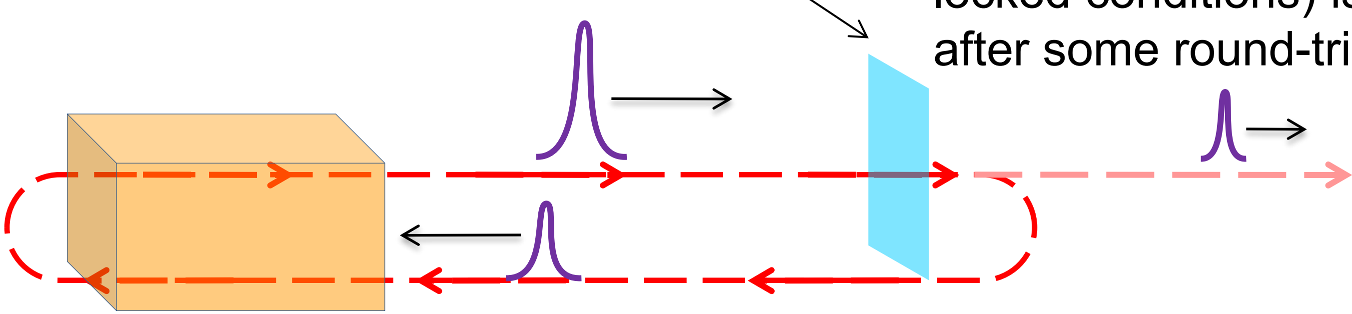
(*a*) A laser essentially consists of a laser medium sandwiched between two mirrors, one of which is partly transmissive. If the amplification of light by the laser medium is greater than the energy loss, light is emitted through the end mirror. (*b*) Many different modes can exist within the laser cavity, under the condition that the cavity length must equal an integer number of wavelengths. Each mode has a different frequency and wavelength. (*c*) In a mode-locked laser the electric field associated with the different modes must add constructively at one point and destructively elsewhere to create a high-intensity spike.

Modes couplés dans la pratique

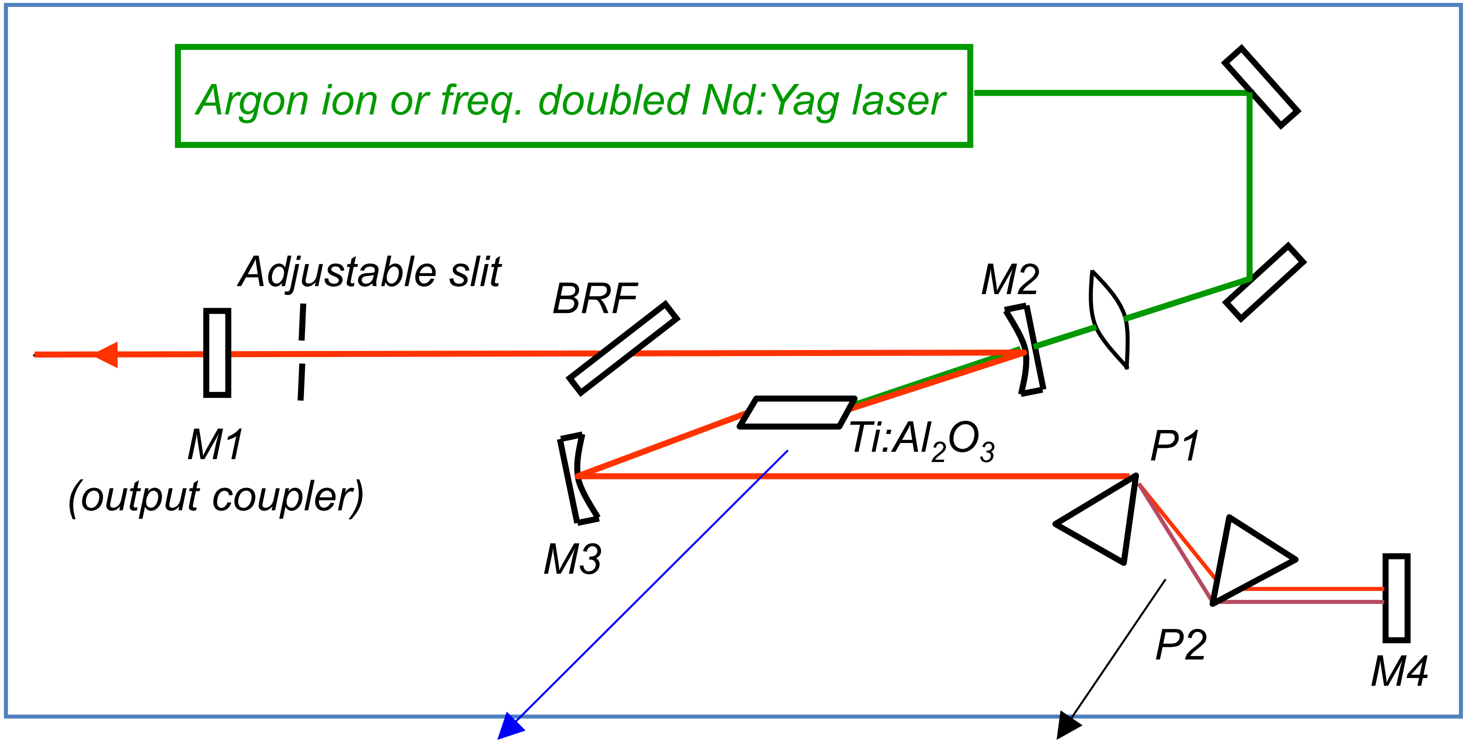


Q-modulating element (1-2%) and pulse round-trip in the resonator are synchronized: actively or passively (automatically)

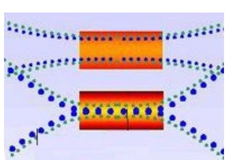
- the synchronized bunch of light is amplified, out-of-phase emission is supressed
- a single travelling pulse (= mode-locked conditions) is established after some round-trips



Schematics of a Femtosecond Laser

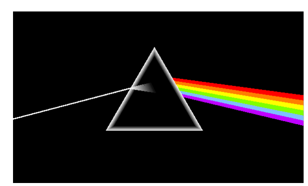


Astigmatismus, dispersion and Kerr lens effect



$\tau_{blue} > \tau_{red}$

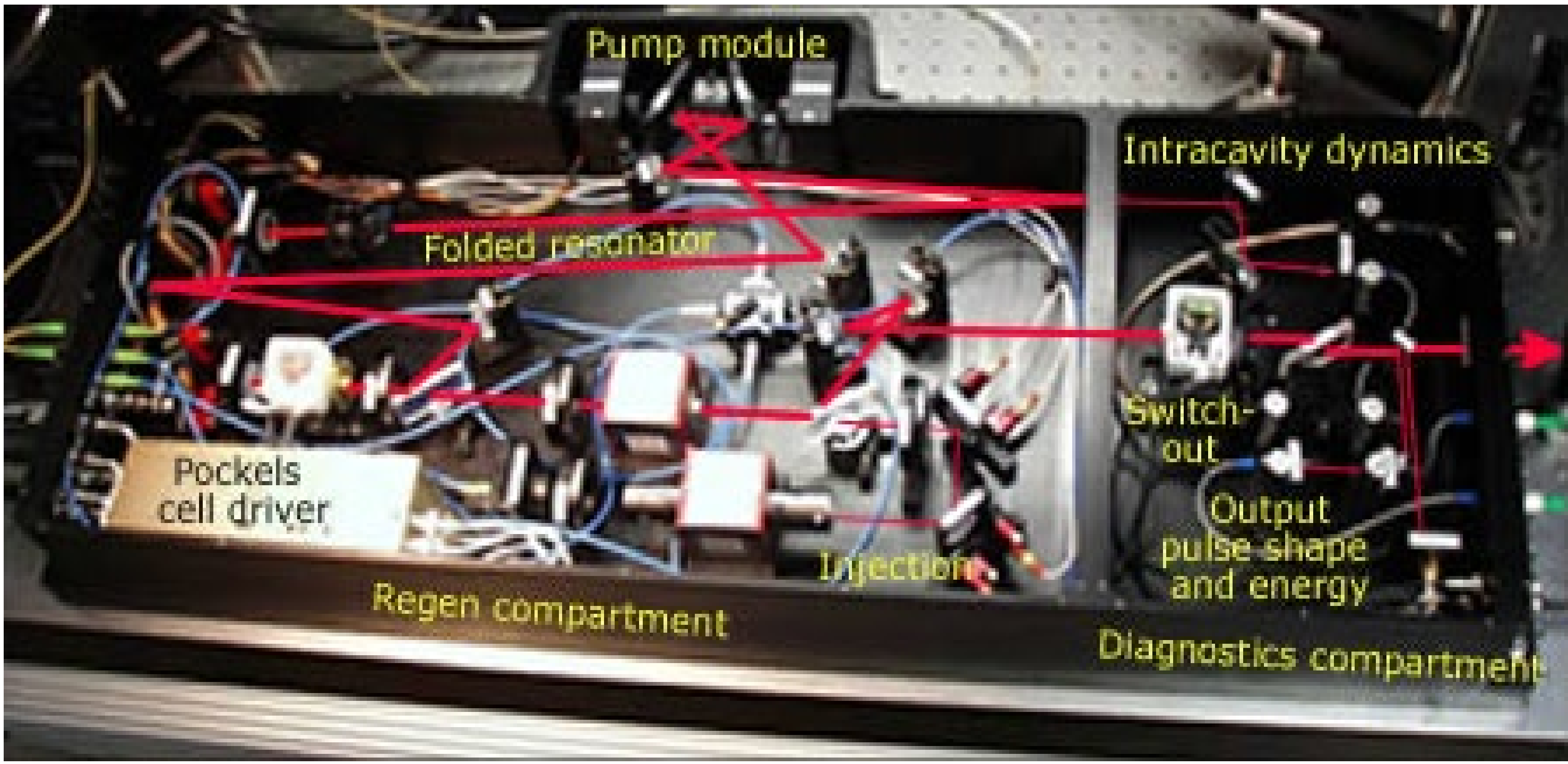
Dispersion compensation



$\tau_{red} > \tau_{blue}$

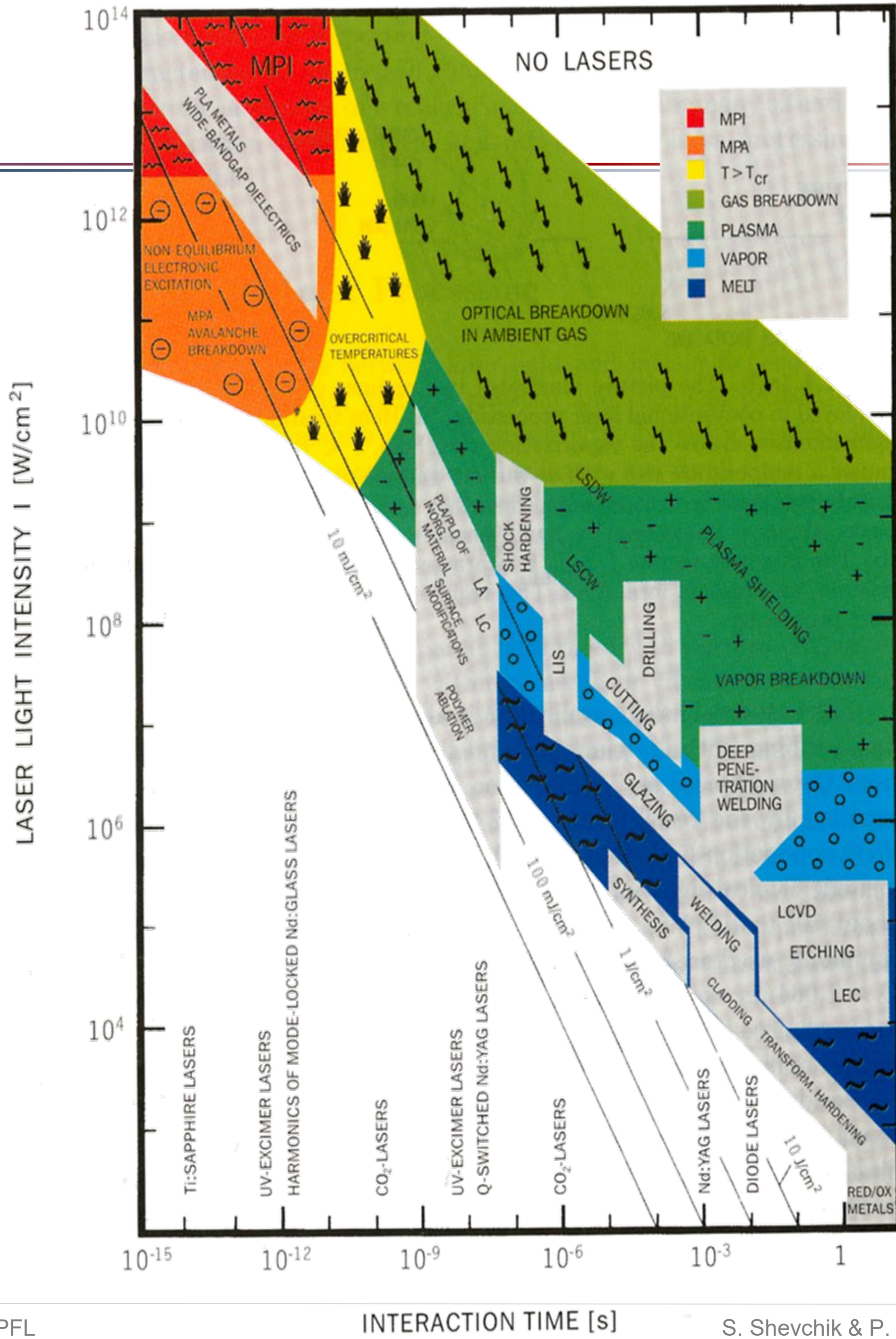
→ minimum pulse width: ~30 fs, special thin crystal and chirped mirrors: 4-5 fs

Femtosecond laser with amplifier



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

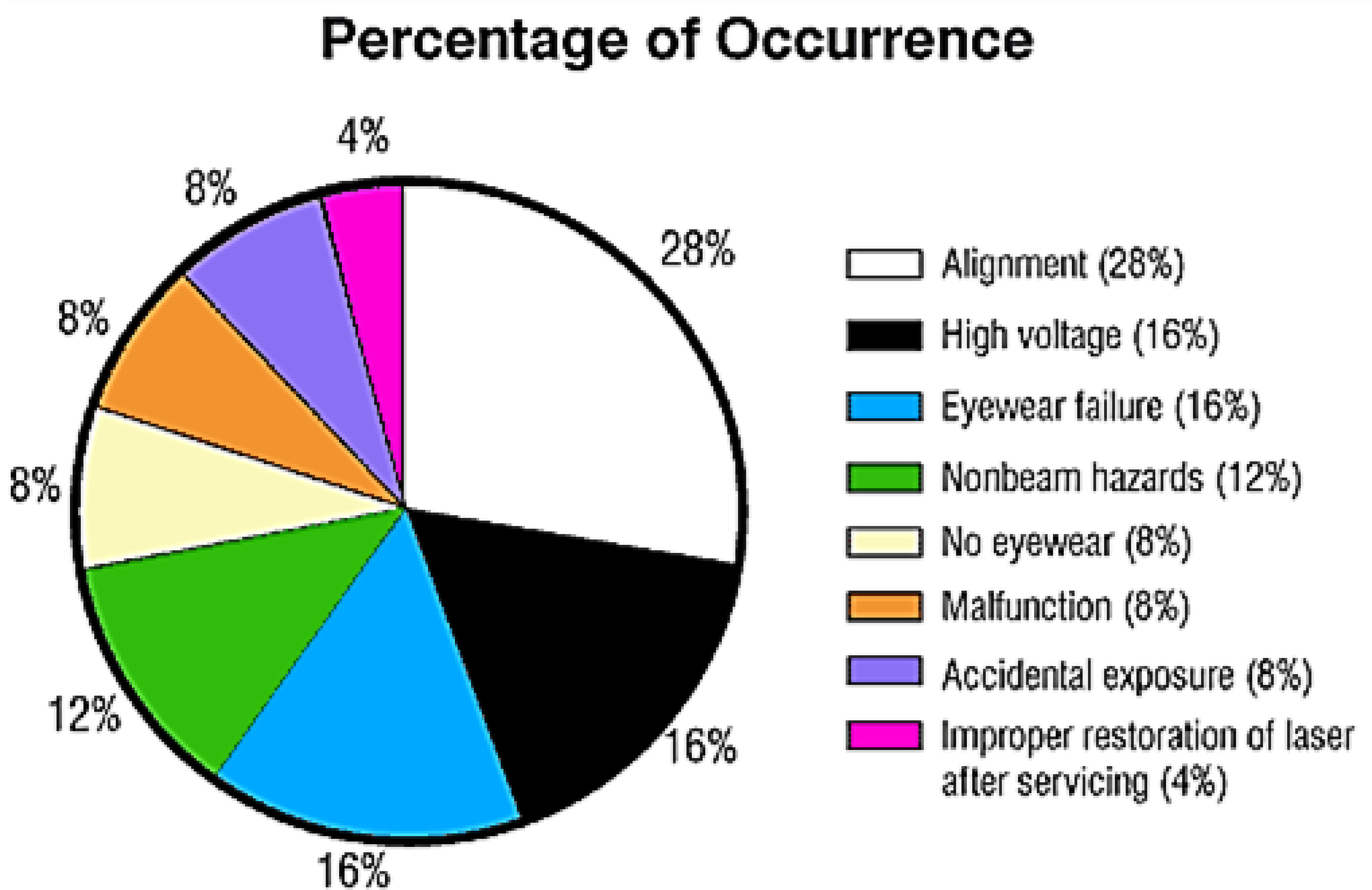
Content

Content

- Laser dangers & hazards
- Insight into the eye physiology
- Classification of Lasers
- Protective measures
  - awareness
  - personal protection
  - protection of people around

Laser Dangers & Hazards

Causes of Laser Accidents



Non-eye Dangers

- Skin Burns
- Fire
- Electrical shock
- Chemicals required for operation of the laser:
  - liquid organic dyes
  - excimer gases (F_2, Cl_2,..)
- Dangerous gases due to decomposition/burning of irradiated material
- High pressure lamp explosion (for flash lamp pumped lasers during maintenance)

Laser is an Electric Device

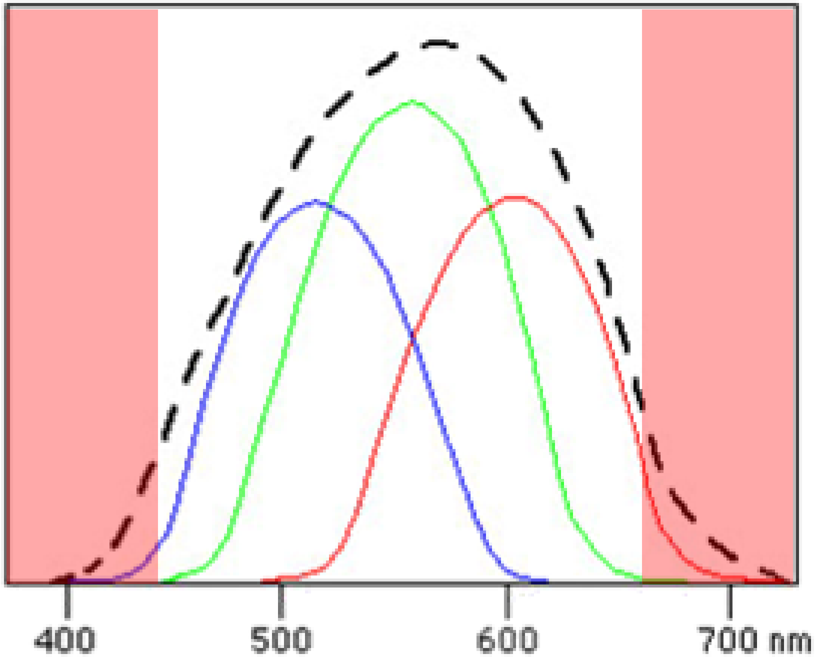
- High-voltage can be present in the laser – apply general safety measures
  - the operation area must be DRY (be careful with cooling water)
  - disconnect equipment the power supply before opening the housing

Dangers to the Skin

- Burns
  - 1W laser can cause burns, but protective reaction can be fast enough
  - for 5W laser reaction time is not enough
- UV lasers can have cancerogenic effect on skin (especially 248 nm – KrF excimer)

Eye Physiology

Spectral Sensitivity of the Eye



Spectral sensitivity of cones and rods in the human eye

Visible range: ~400 – ~750 nm

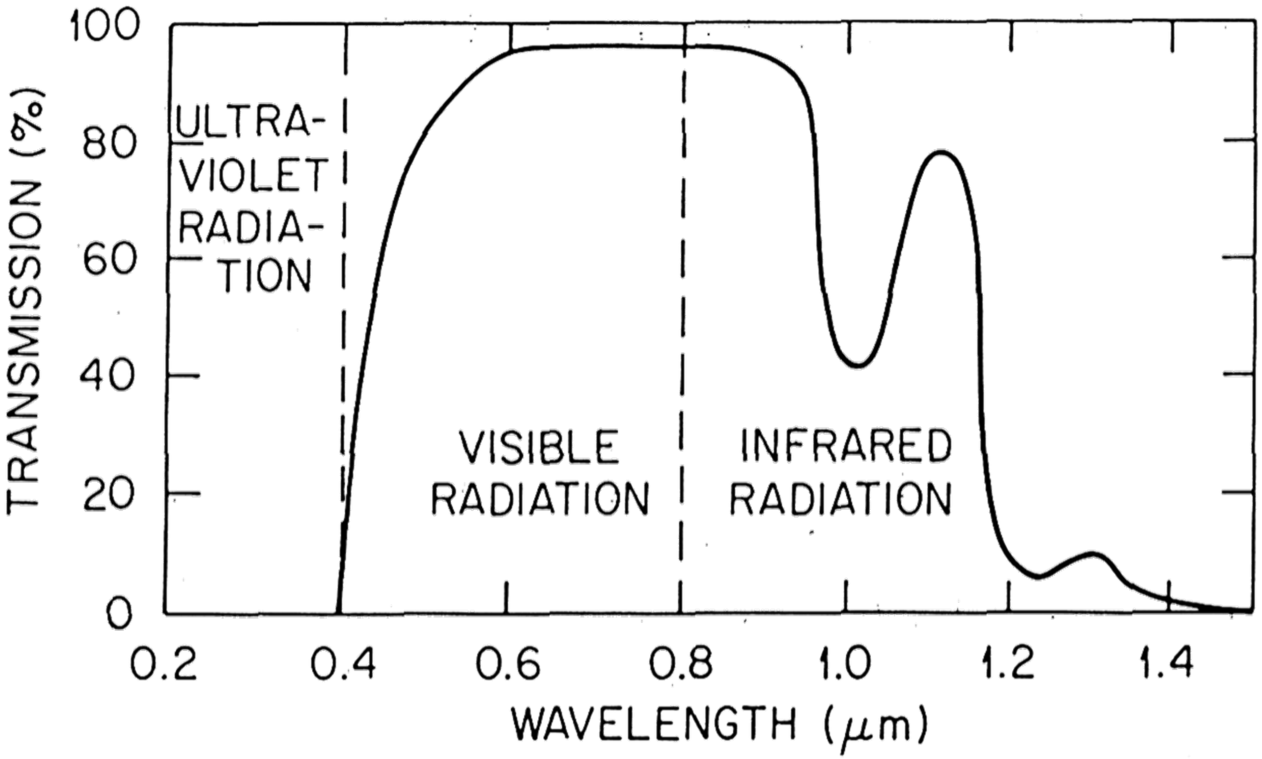
Laser in the range close to the visibility regions (350- 400 nm and 700-850 nm) are very dangerous.

The beam is visible and appear to be very weak - though in reality the power may be very high.

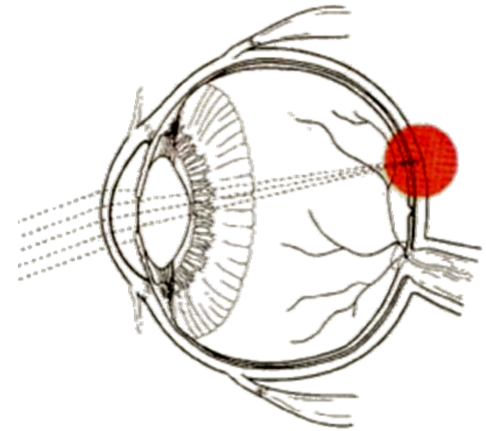
Typical examples:

pumping diodes for Nd:YAG (808 nm, P > 20-50 W)

Transmission of the Eyes Tissues

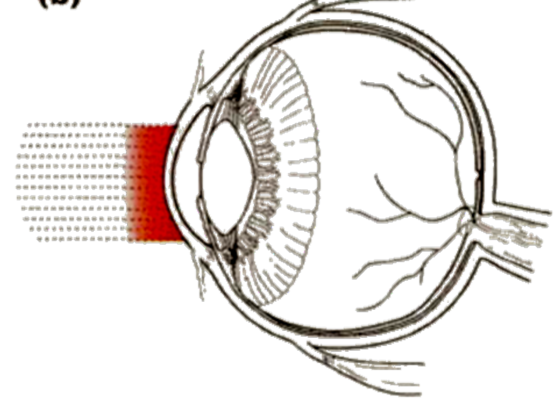


Retinal hazard region:
400 – 1400 nm



Cornea/lens hazard:
<400 nm and >1400 nm

(b)



Transmitted wavelength range is significantly broader than visible range → retinal hazard !!!!

Do not get injured!

Followed safety rules

Cornea Damage

BAD

Retina Damage

WORSE

What to do in case

In case of injury optician should be visited immediately !!!!

Experience has demonstrated that most laser injuries go unreported by the injured person for 24–48 hours.

This is a critical time for treatment of the injury!

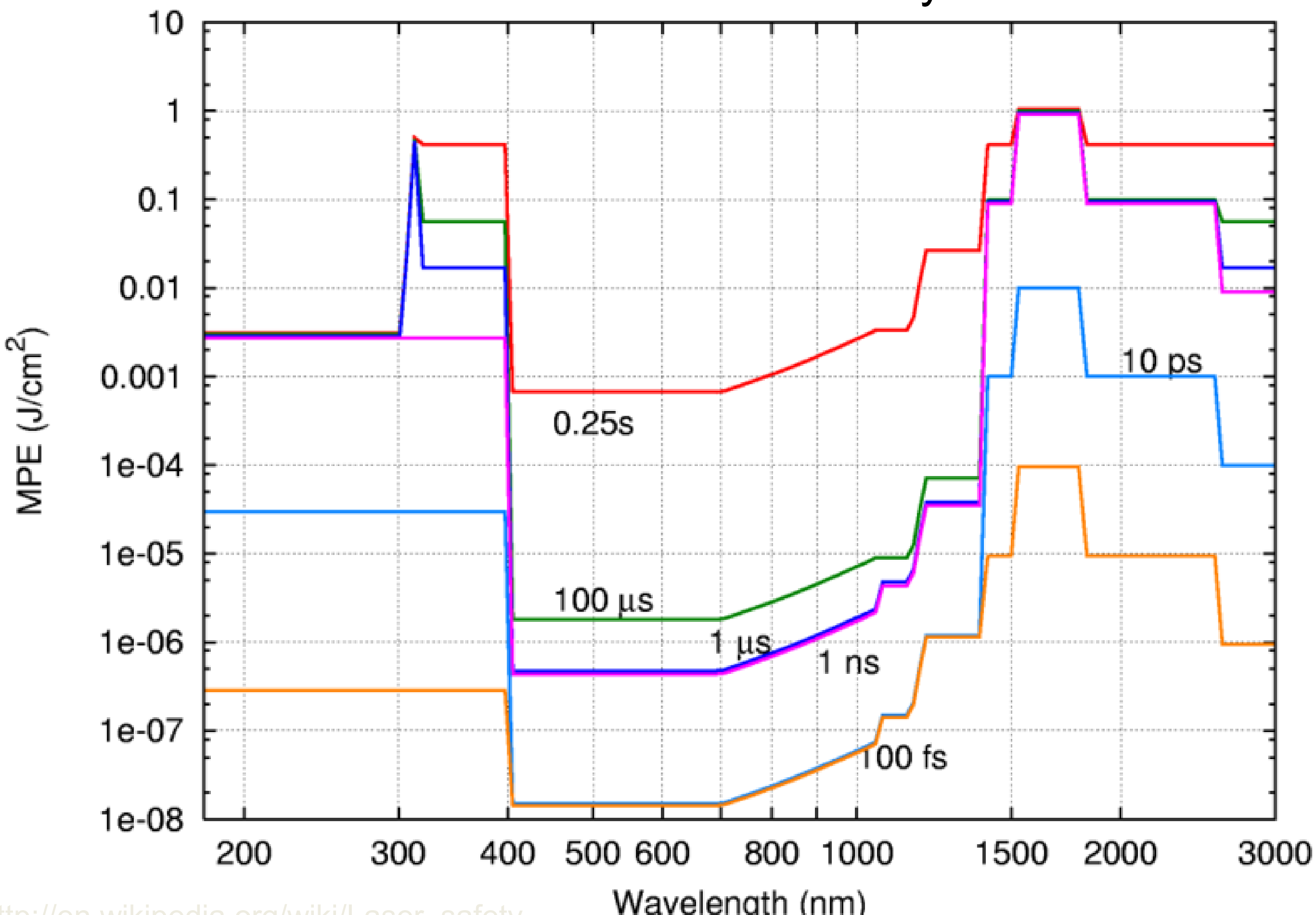
How do you know if you have an eye injury?

- Exposure to infrared high-power laser causes a burning pain in the eye (to the cornea or sclera)
- Exposure to visible lasers causes a bright color flash of the emitted wavelength and afterwards an image of the complementary color
- Exposure to short pulsed infrared lasers may go undetected or may cause a popping sound followed by visual disorientation

Maximum Permissible Exposure

MPE: highest power or energy density (in W/cm^2 or J/cm^2) of a light source that is considered safe – depends on the exposure duration

MPE for the human eye



Reference: http://en.wikipedia.org/wiki/Laser_safety

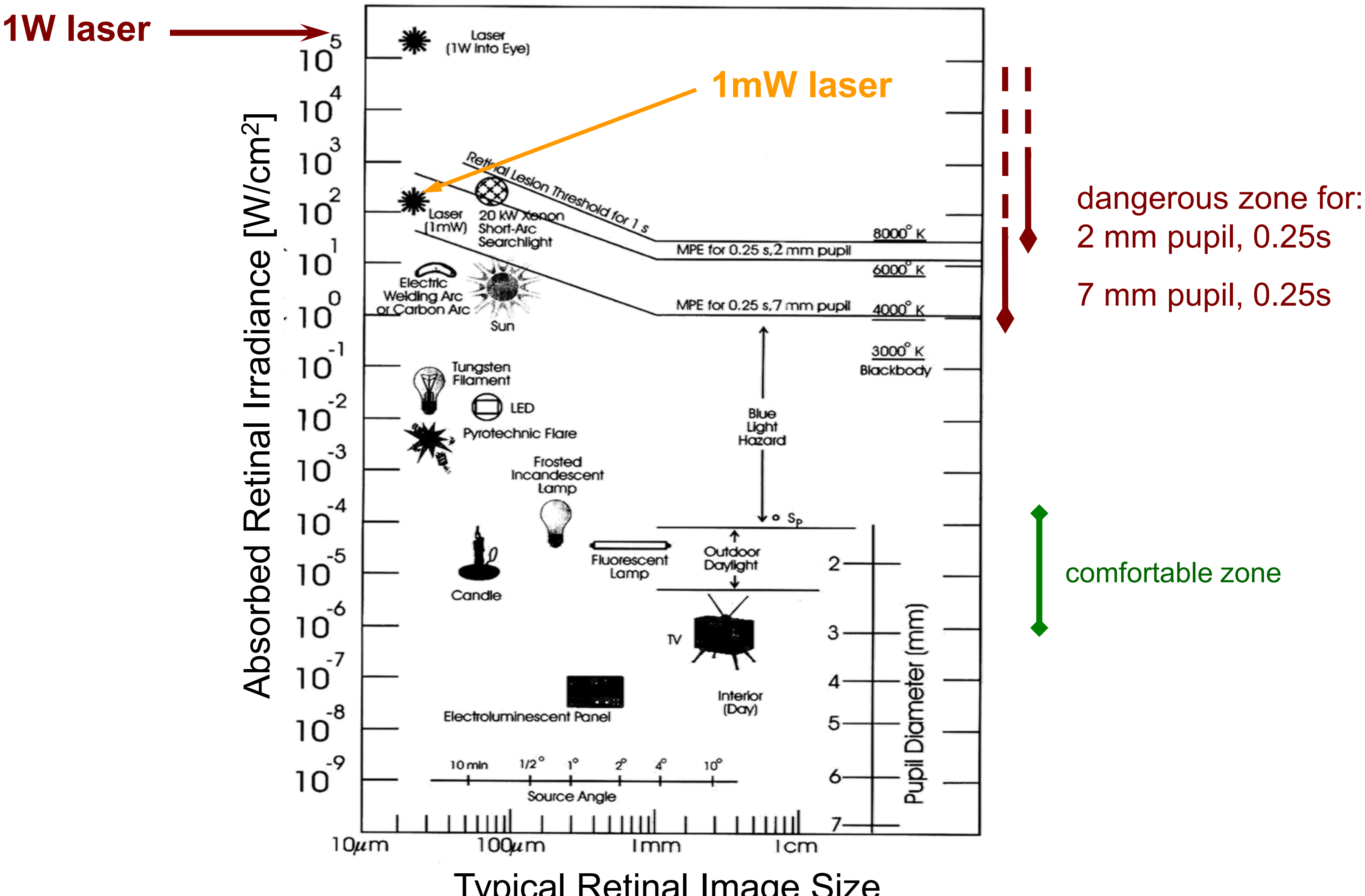
MPE and Exposure Duration

$\Delta\tau$=0.25s is a typical reaction time to close the eye lid (blinking)

For visible lasers this is considered a critical period during which MPE should not be reached.

For invisible (e.g. infrared laser) 10s exposure is usually taken as the critical period – so the protection need to be stronger.

Retinal Irradiance for Various Sources



Classification of Lasers

Laser Safety Standards

There are two principle international laser safety standards:

- International Electrotechnical Commission
  IEC 60825
- American National Standards Institute
  ANSI Z136

There are also European Norms for Safety Eyewear:

- EN 207 and EN 208

Old and New System

Revised system (introduced in 2002) - IEC 60825-1

- Class 1
- Class 1M
- Class 2
- Class 2M
- Class 3R
- Class 3B
- Class 4

new classification takes into account knowledge about the lasers and laser safety accumulated since introduction of the first classification

↑

Arabic numerals

"Old" classification system (developed in early 1970s), still used in US (ANSI Z136)

- Class I
- Class II
- Class IIa
- Class IIIa
- Class IIIb
- Class IV

How to differentiate?

Roman numerals →

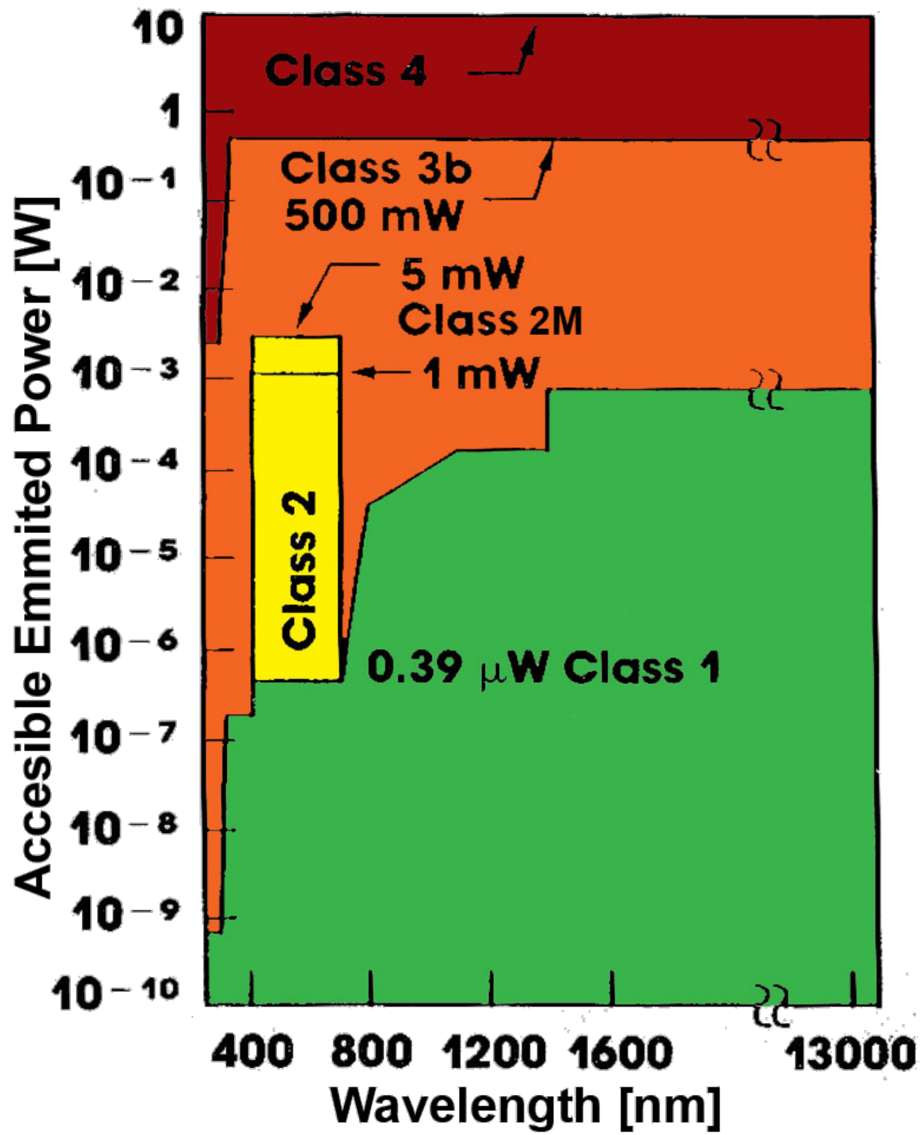
Laser Classes

Class	Hazard	Comments
1	without danger	if view not intentional
1M	retinal burn	dangerous if viewed **through magnifying optics** (microscope, telescope, etc.)
2	retinal burn	danger if exposure **>0.25s** (reaction time)
2M	retinal burn	danger if exposure **>0.25s** and **viewed** through the **optical device**
3R	retinal burn	direct view is dangerous (5mW limit for visible lasers)
3B	retinal burn & other biological effects	direct view is dangerous, diffuse reflections could be dangerous (0.5W limit for visible lasers)
4	retinal burn & other biological effects & skin burn	**direct** view **and diffuse** reflections are **dangerous**. Extreme care!

Laser Classes

Approximate assignment of the laser classes for continuous wave lasers

Depend on laser power, emitted wavelength, pulse duration.



Maximum Emission Limits for Class 1

Accessible emission limits for Class 1 laser products

Wavelength λ (nm)		Emission duration t (s): <10^-9	10^-9 to 10^-7	10^-7 to 10^-6	10^-6 to 1.8 x 10^-5	1.8 x 10^-5 to 5 x 10^-5	5 x 10^-5 to 10	10 to 10^3	10^3 to 10^4	10^4 to 3 x 10^4
180 to 302.5		2.4×10^{4} W	2.4×10^{-5} J							
302.5 to 315			$7.9 \times 10^{-7} C_1$ J $(t < T_1)$ / $7.9 \times 10^{-7} C_2$ J $(t > T_1)$					$7.9 \times 10^{-7} C_2$ J		
315 to 400			$7.9 \times 10^{-7} C_1$ J					7.9×10^{-3} J	7.9×10^{-6} W	
400 to 550	or	200 W	2×10^{-7} J			$7 \times 10^{-4} t^{0.75}$ J		3.9×10^{-3} J		3.9×10^{-7} W
		10^{11} W.m^{-2} sr^{-1}	$10^{5} t^{0.33}$ J.m^{-2} sr^{-1}					2.1×10^{5} J.m^{-2} sr^{-1}		21 W.m^{-2} sr^{-1}
550 to 700	or	200 W	2×10^{-7} J			$7 \times 10^{-4} t^{0.75}$ J $(t < T_2)$ / $3.9 \times 10^{-3} C_3$ J $(t > T_2)$				$3.9 \times 10^{-7} C_3$ W
		10^{11} W.m^{-2} sr^{-1}	$10^{5} t^{0.33}$ J.m^{-2} sr^{-1}					$(t < T_2)$ $3.9 \times 10^{4} t^{0.75}$ J.m^{-2} sr^{-1} / $2.1 \times 10^{5} C_3$ J.m^{-2} sr^{-1} $(t > T_2)$		21 C_3 W.m^{-2} sr^{-1}
700 to 1050	or	200 C_4 W	$2 \times 10^{-7} C_4$ J			$7 \times 10^{-4} t^{0.75} C_4$ J			$1.2 \times 10^{-4} C_4$ W	
		$10^{11} C_4$ W.m^{-2} sr^{-1}	$10^{5} t^{0.33} C_4$ J.m^{-2} sr^{-1}					$3.9 \times 10^{4} t^{0.75} C_4$ J.m^{-2} sr^{-1}	$6.4 \times 10^{3} C_4$ W.m^{-2} sr^{-1}	
1050 to 1400	or	2×10^{3} W	2×10^{-6} J				$3.5 \times 10^{-3} \times t^{0.75}$ J		6×10^{-4} W	
		5×10^{11} W.m^{-2} sr^{-1}	$5 \times 10^{5} t^{0.33}$ J.m^{-2} sr^{-1}					$1.9 \times 10^{5} t^{0.75}$ J.m^{-2} sr^{-1}	3.2×10^{4} W.m^{-2} sr^{-1}	
1400 to 1530		8×10^{4} W	8×10^{-5} J	$4.4 \times 10^{-3} t^{0.25}$ J				8×10^{-4} W		
1530 to 1550			8×10^{-3} J		$4.4 \times 10^{-3} t^{0.25}$ J					
1550 to 10^{5}			8×10^{-5} J	$4.4 \times 10^{-3} t^{0.25}$ J						
10^{5} to 10^{6}		10^{7} W	10^{-2} J	$0.56 t^{0.25}$ J				0.1 W		

(See notes page 36)

←pulse length

↑ wavelength

complexity of the real world !!! (meant mainly for manufacturers)

Prevention & Protection

Protection Measures

- Warning signs and flashing lights
- Interlocks
- Exposed areas restriction
- Eye protection: goggles/glasses
- Skin protection: gloves, full face mask (for UV lasers)
- Most important: think about consequences before you act !!!

BE CAREFUL

THIS MACHINE HAS NO BRAIN USE YOUR OWN

Resposibility

- Operator of the laser has the primary responsibility !!!!
- If you have any concerns, questions or lack of knowledge contact the superior or (laser) safety responsible

Warning Signs

Labels used to mark the lasers

Classes **I** to **IIIa**

Classes **IIIb** to **IV**

Warning Signs

Standard “Laser Hazard” warning sign.

Must be present on lasers starting from Class II

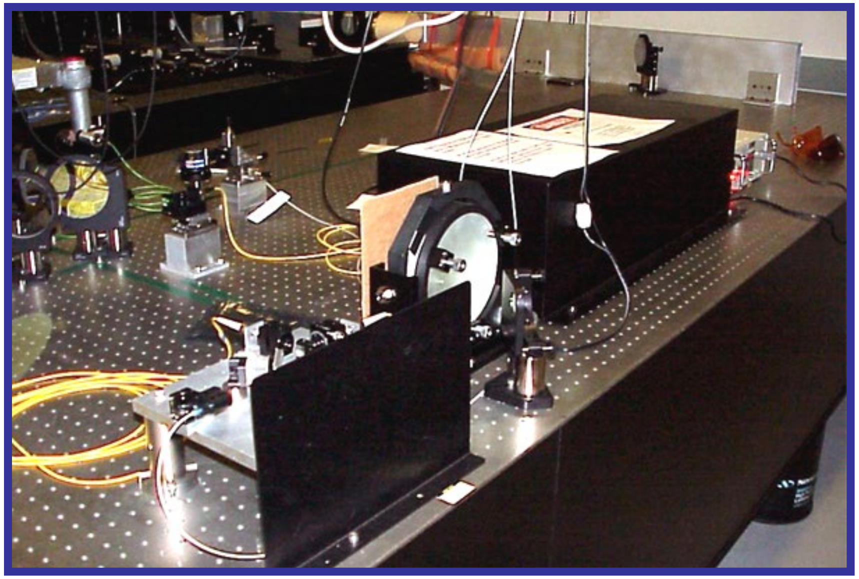
Normally also placed to mark the dangerous area (e.g. at entrance doors, etc.)

Warning sign at the beam exit of the laser body

Precautions

- Avoid reflective materials in the laser lab
  - polished objects
  - glossy paints
  - jewellery; watches
- Use beam barriers
  - beam blockers to absorb unused beams/reflections
  - redundant blocker behind your set-up in case beam passes through
  - curtains/screens to protect the others

Protective Barriers (local)



Protective Screens (whole area)

KENTEK
"Laser People Helping Laser People"®

Precautions

- Never point the beam to somebody
- Never look along the beam axis or at the level of the beam path in general
- Don't install beam axis in eye height
  - laying (unconscious) ca. 0.1 m
  - sitting ca. 1.2 m
  - standing ca. 1.7 m
- PC for data recording / analysis should be placed in the protected area (common risk source!!!)

Eyewear

Eyeware

Protective glasses / goggles are laser specific – they are disigned to block certain wavelength and withstand certain power

Pay attention that the glasses are suitable for the laser you use !!!

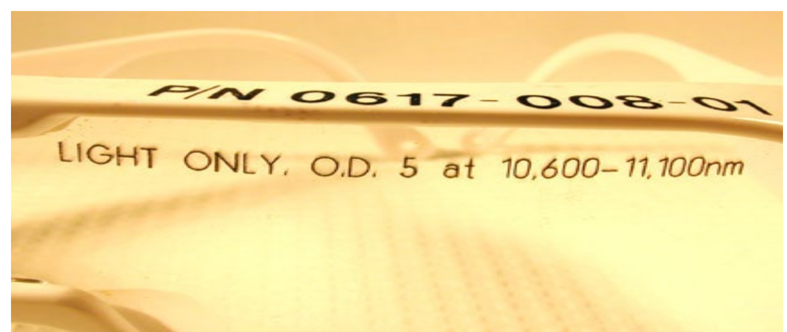
Optical Density

Protective properties of the protective eyewear is typically marked in OD units.

Optical Density (OD) – measure of absorption in logarithmic scale

$$D_\lambda = \log_{10}(I_{incident} / I_{transmitted})$$

OD	% Transmission
0	100%
1	10%
2	1%
3	0.1%
4	0.01%
5	0.001%
6	0.0001%



Selecting Eye Protection

How to determine minimum required Optical Density (OD):

$$D_\lambda = \log_{10}(H_p/MPE)$$

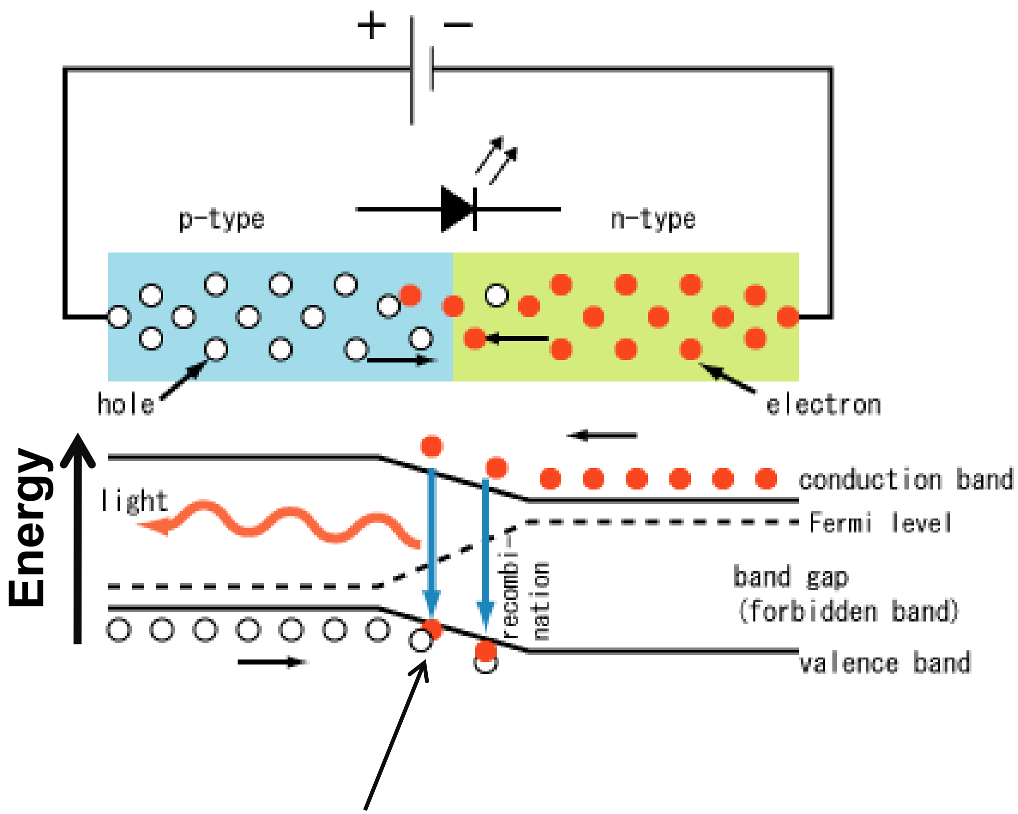
- D_λ = optical density at wavelength λ
- H_p = potential eye exposure (given by laser and set-up)
- MPE = Maximum Permissible Exposure for used laser type (λ, τ)

Eye Protection

- Remember: protective laser glasses are "the last hope" in case of accidental exposure and also might fail (especially for high power lasers)
  - Be sure to take all possible protective measures to avoid such exposures in principle

LEDs

Light Emitting Diodes



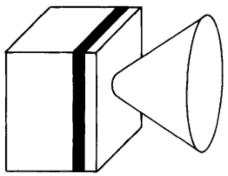
Recombination of electrons and holes in the p-n junction liberates energy, emitted as light.

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

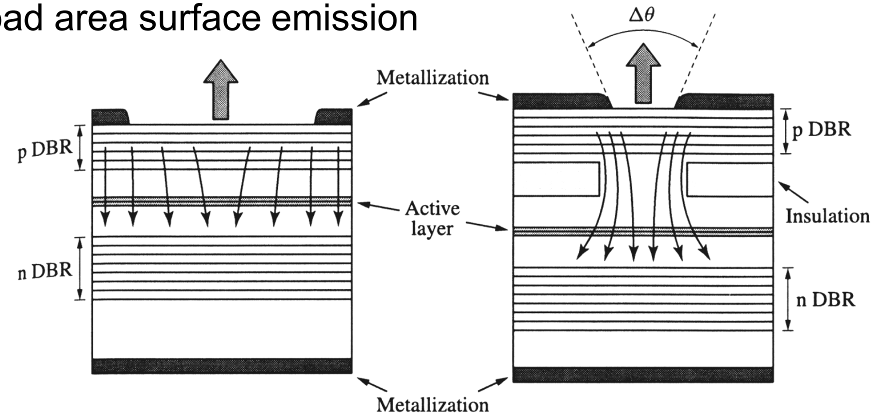
Light Emitting Diodes

Surface emitting LEDs

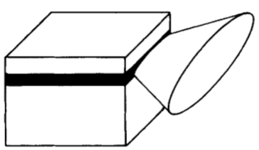


Broad area surface emission

small area surface emission

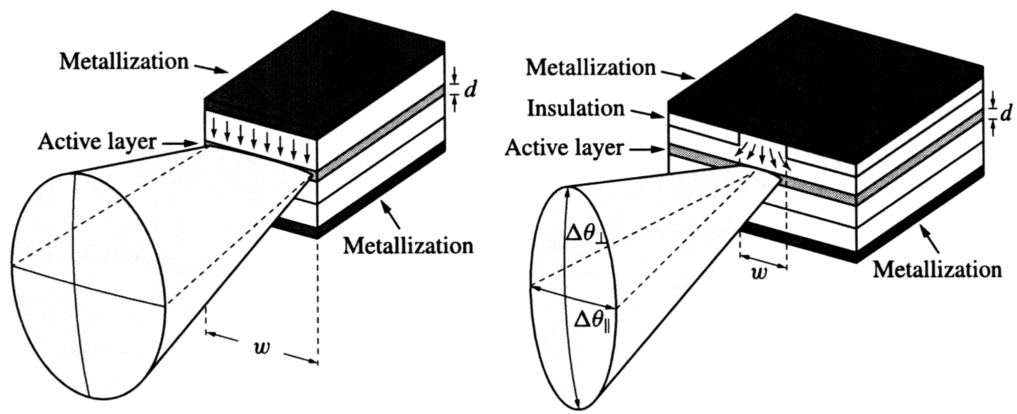


Edge emitting LEDs



Broad area edge emission

Strip geometry edge emission



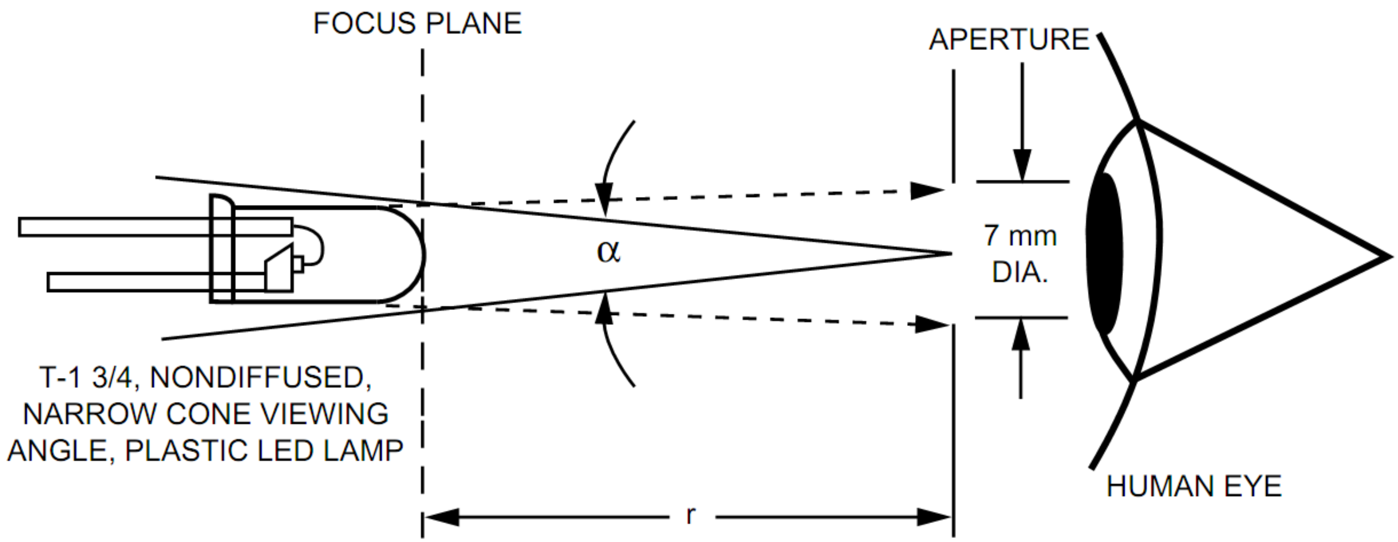
Emitting surface of the LED can be quite small:

dia.~10 µm – for surface emission

1 µm x 10 µm – for egde emitting LED

LED Safety Considerations

- Modern illumination LEDs can reach multi-watt light output.
- Combined with small source area this may result in very high brightness light source.



European CENELEC EN60825-1 Standard specifies LED evaluation method based on source luminous intensity (lm/sr) and viewing angle of the LED

Some brigth LEDs are classified as Class 2 devices (can cause retinal burn!!!)

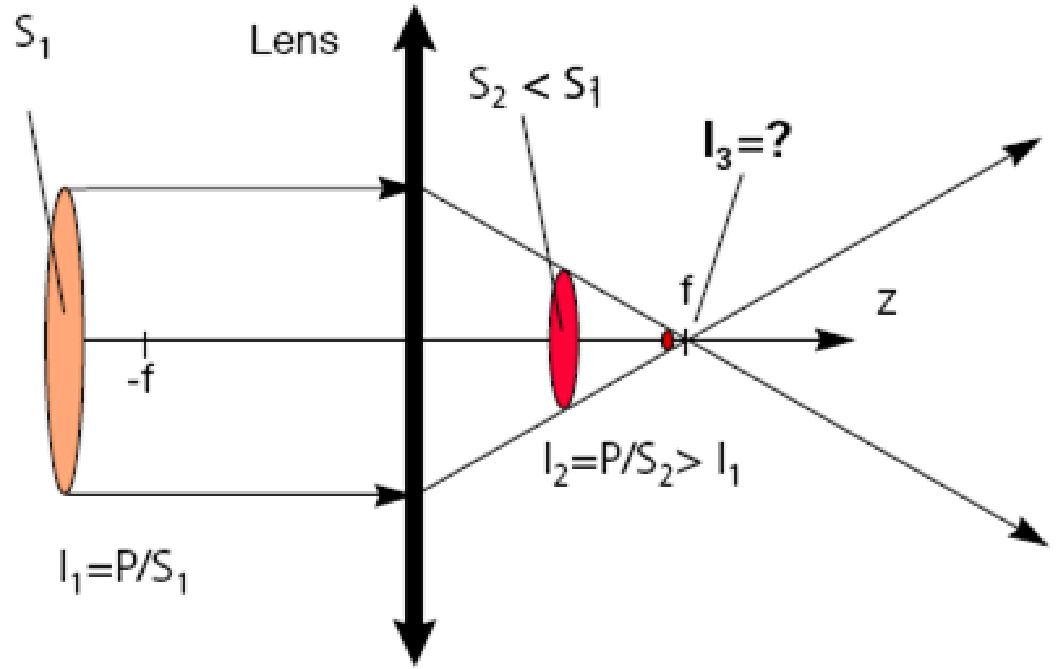
The END

Content

- Gaussian beams
- Focusing
- Mask imaging
- Laser diode beam forming
- Optical fibers
- Interferometric methods

Imaging and Gaussian beams

Geometrical "focusing"

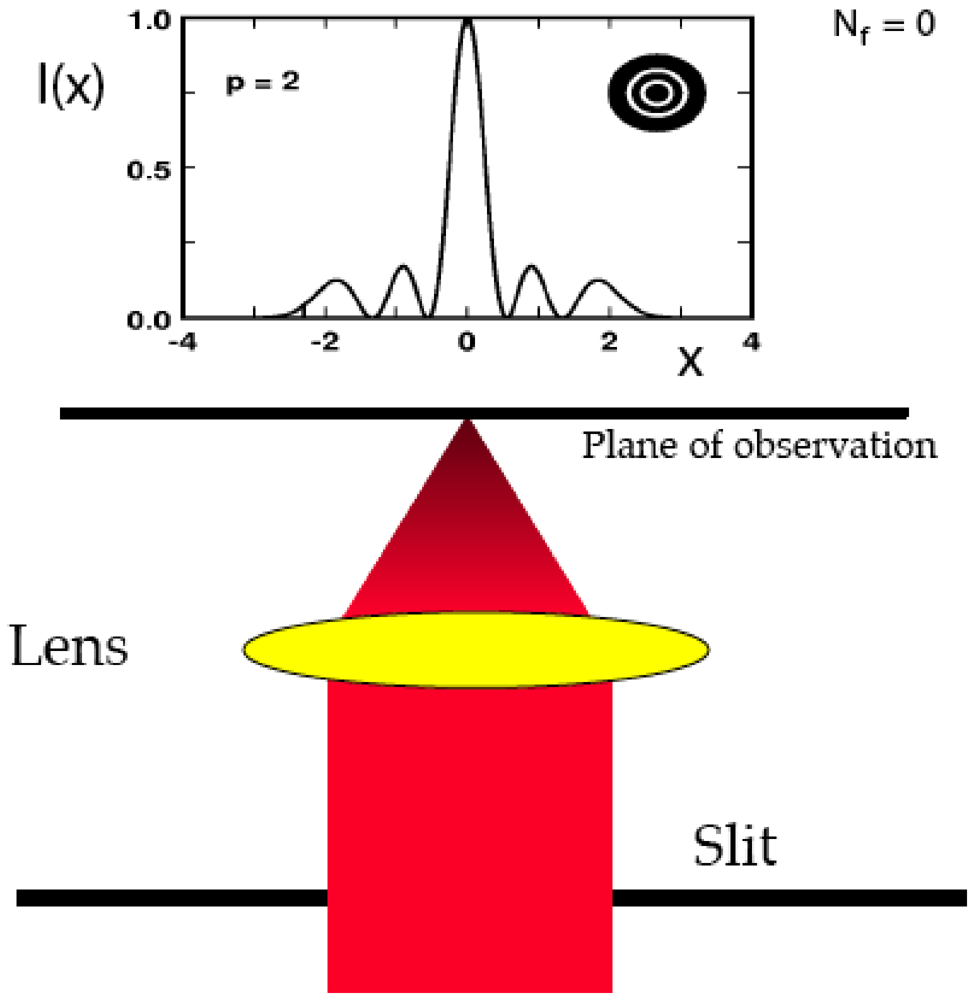


The surface of the beam vanishes at the exact focus location

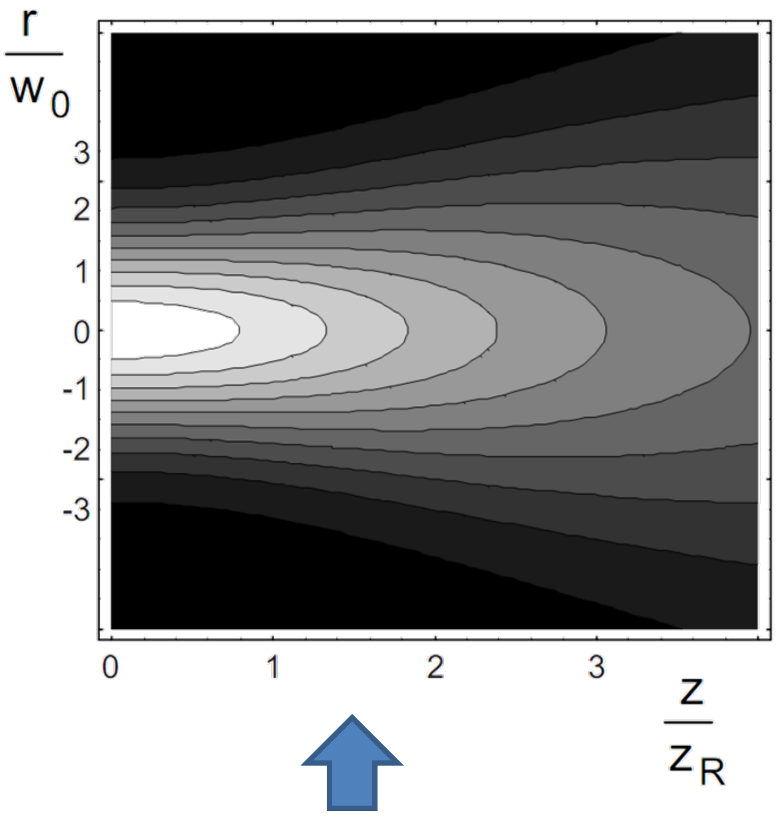
“Real World” Focusing

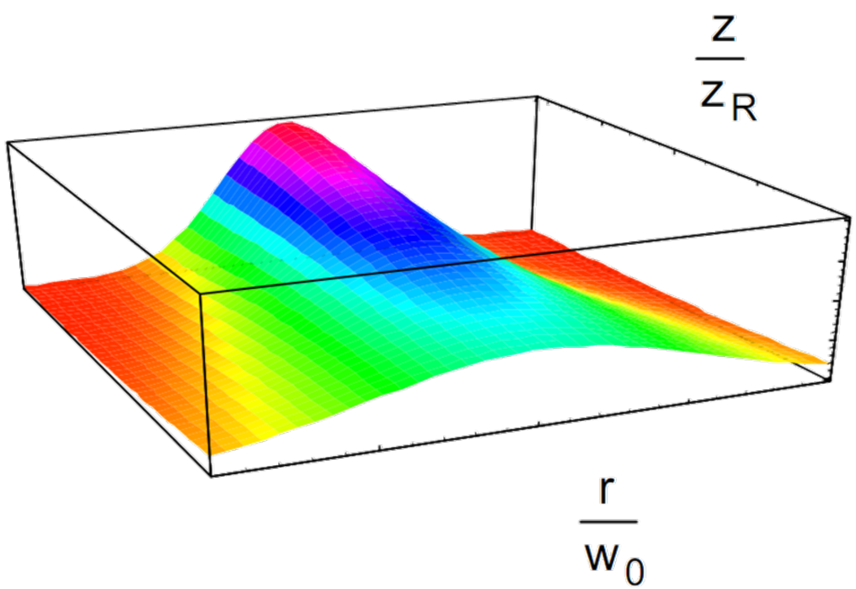
$$I(x) \quad \mu \left(\frac{Sin(kx)}{kx} \right)^2$$

Diffraction with a slit aperture



Intensity Distribution in Gaussian Beam

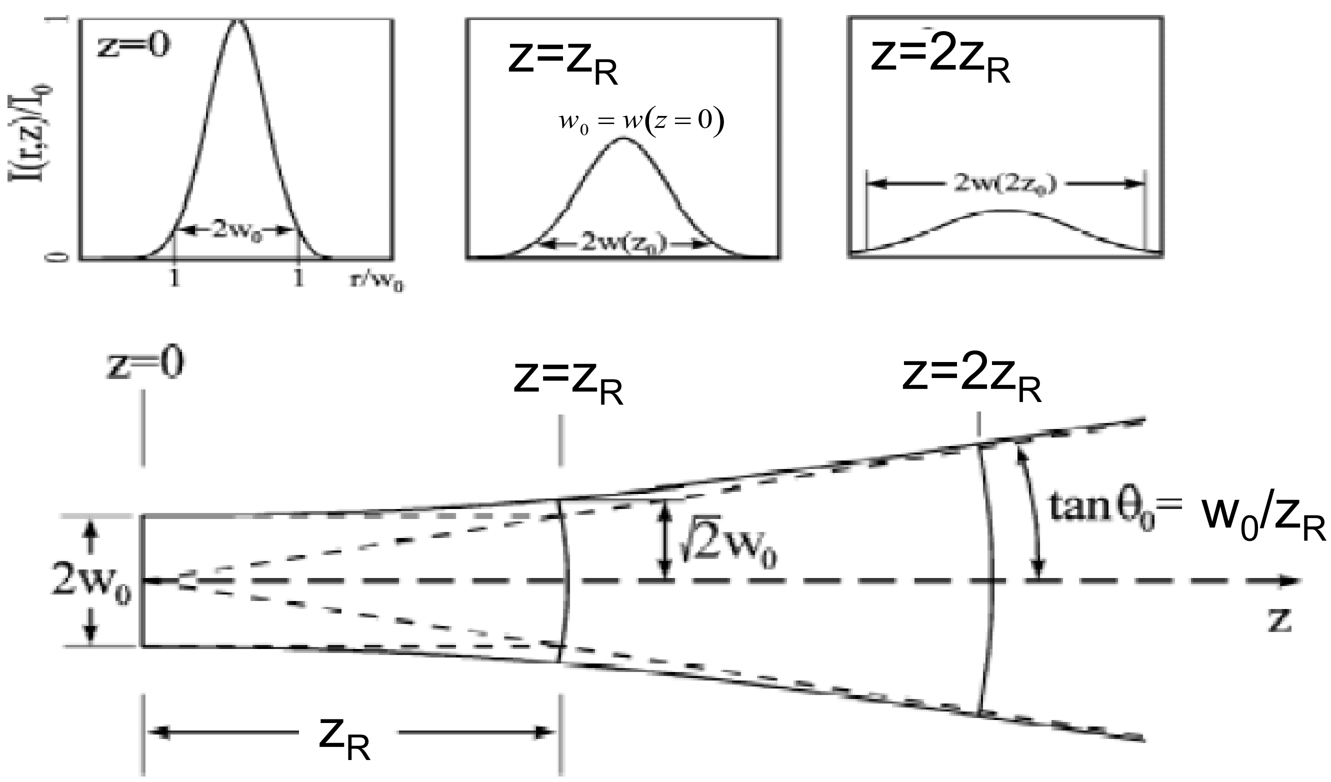




at each z-position, radial intensity distribution is Gaussian

Definition of Gaussian Beam

Fundumental mode intensity $$I(r,z) = I_0 e^{-2\left(r/w(z)\right)^2}$$



Definitions of the Beam Size

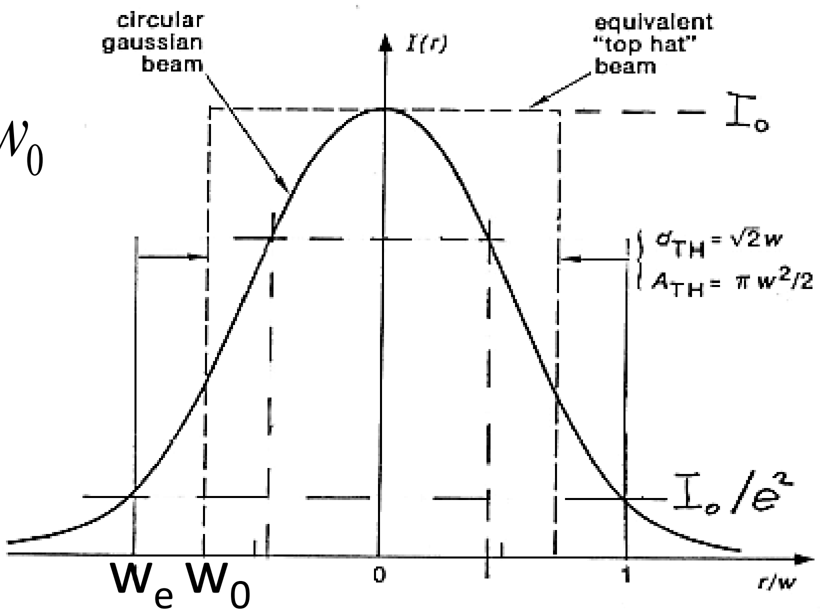
Definitions of the beam size (waist):

$$I(w_0,0) = I_0/e$$

$$I(w_e, z_e) = I_0 / e^2, \quad w_e = w(z_e) = \sqrt{2} w_0$$

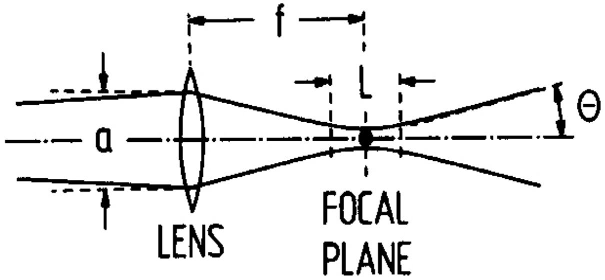
Total intensity of the beam:

$$P_0 = 2\pi \int_0^\infty r I(r) dr = \pi w_0^2 I_0$$



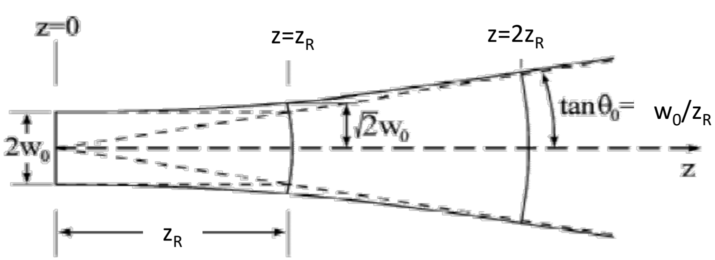
Normalised Gaussian beam profile, with different approximations

Rayleigh Range and Depth of Focus



Waist $$w_0 \approx \frac{2f\lambda}{\pi a} \approx \frac{\lambda}{\theta \cdot \pi}$$

Divergence $$\theta = \frac{w_0}{z_R} = \frac{a}{2f}$$



Rayleigh range definition: *$I(r=0, z=z_R) = I_0/2$*

Rayleigh range value $$z_R = \frac{\pi}{\lambda} w_0^2$$

Depth of focus

$$L = 2z_R = \frac{2\pi w_0^2}{\lambda} = \frac{4f^2\lambda}{\pi a^2}$$

Beam radius at the distance $$w(z) = w_0\sqrt{1 + \left(\frac{z}{z_0}\right)^2}$$

Cross-section of Gaussian Beam

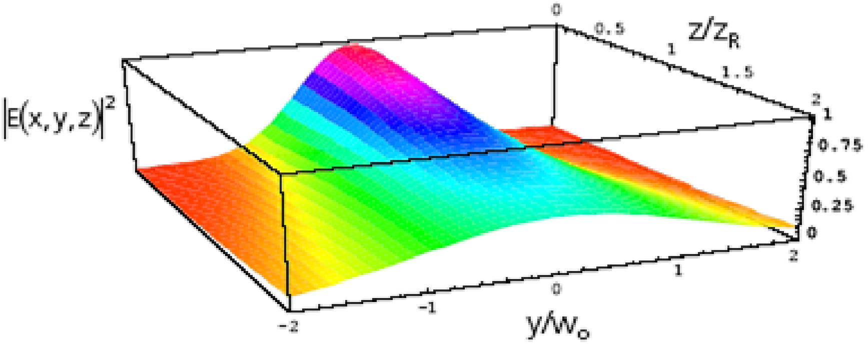
a Gaussian Beam is completely defined by the parameters:

w_0 - waist at focal point

z_R – Rayleigh range

$$w_0 \approx \frac{2f\lambda}{\pi a} \approx \frac{\lambda}{\theta \cdot \pi}$$

$$z_R = \frac{\pi}{\lambda} w_0^2$$

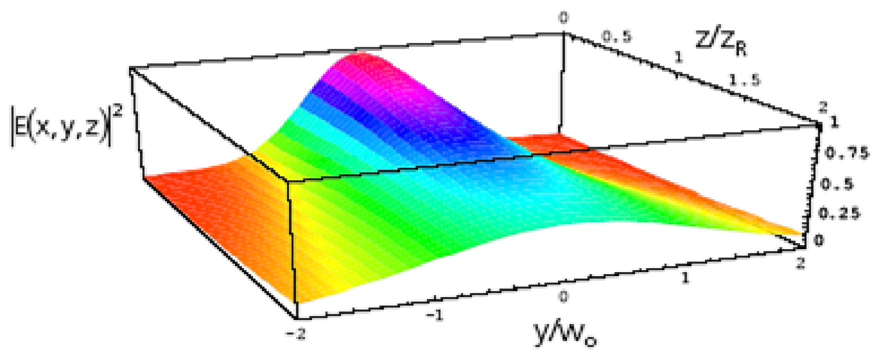


$$I(r,z) = I_0 \left(\frac{w_0}{w(z)} \right)^2 \exp\left[-2 \left(\frac{r}{w(z)} \right)^2 \right]$$

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

Cross-section of Gaussian Beam

$$I(r,z) = I_0\left(\frac{w_0}{w(z)}\right)^2 \exp\left[-2\left(\frac{r}{w(z)}\right)^2\right] \qquad w(z) = w_0\sqrt{1+\left(z/z_R\right)^2}$$



Some examples of properties:

$$I(r=0,z) = I_0\left(w_0/w(z)\right)^2 = \frac{I_0}{1+\left(z/z_R\right)^2}$$

$I(r{=}0,\ z{=}z_R) = I_0/2$ After one Rayleigh length

$I(r{=}0,\ z{>>}z_R) = I_0(z_R/z)^2$ In the far field

Beam Parameter Product (BBP)

As $\theta = w_0/z_R$ et $z_R = \pi w_0^2/\lambda$

BBP

$$\theta \cdot w_0 = \frac{\lambda}{\pi} = const.$$

The product of the radius times the divergence is **minimal for the Gaussian beam** and contains only the parameter wavelength λ .

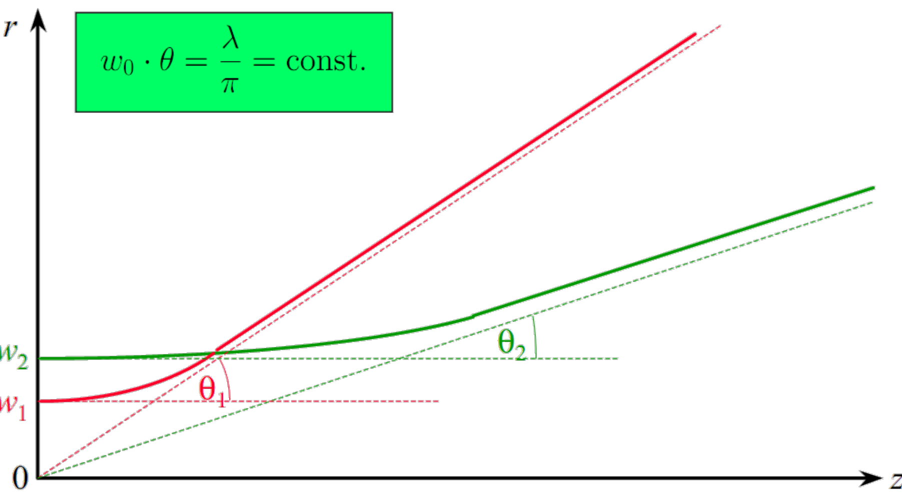
This product is invariant during propagation and also focusing.

For a real laser beam:

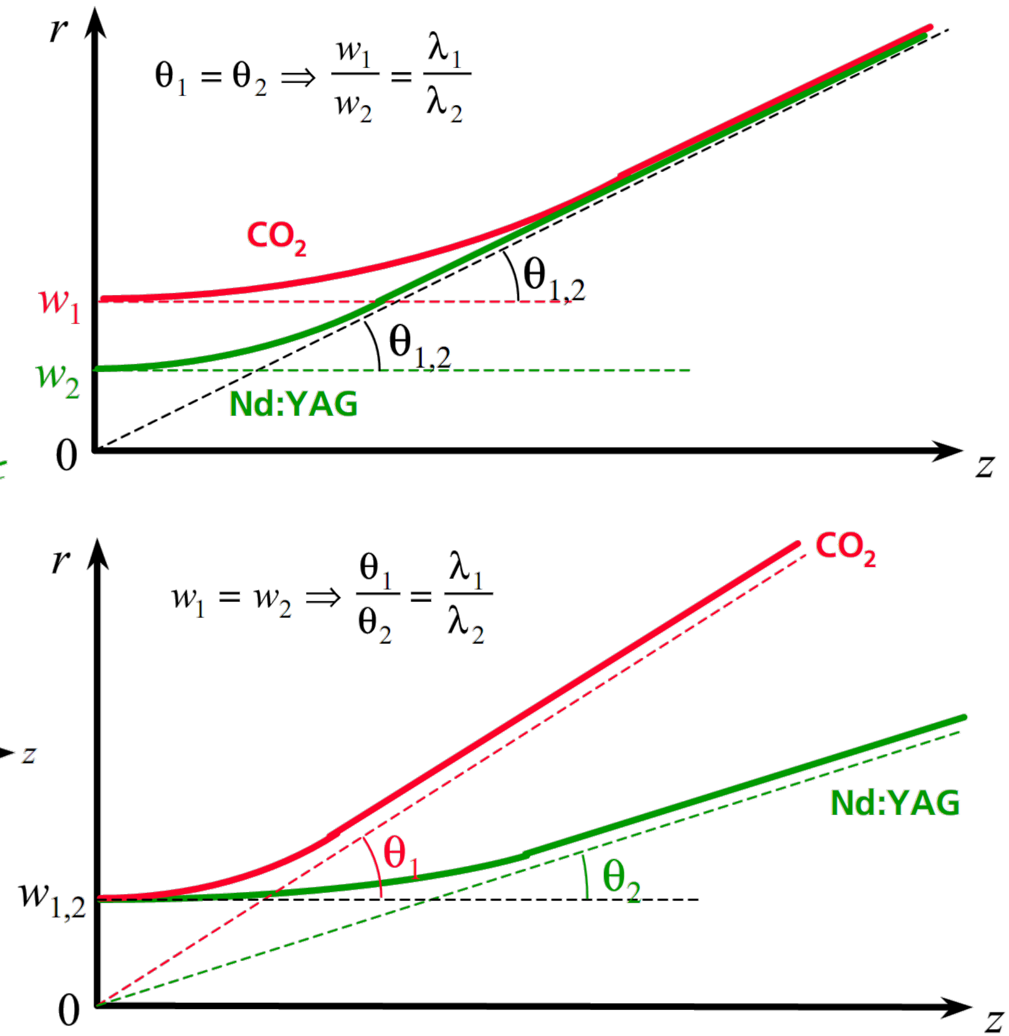
3 mm x mrad for a CO_2 laser $\lambda = 10{,}6\ \mu m$
0,3 mm x mrad for a Nd-YAG laser $\lambda = 1{,}06\ \mu m$

Focusing of a Gaussian Beam

BBP stays constant for the same beam

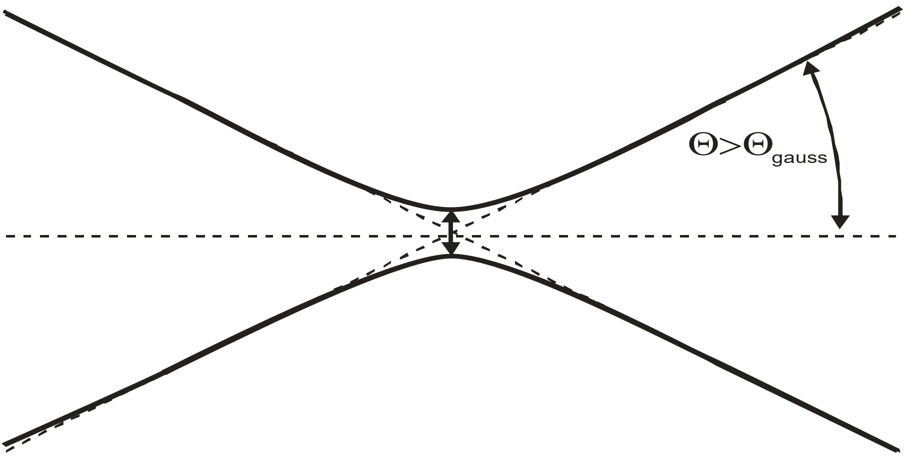


Nd:YAG and CO_2 laser



M^2 Factor

gaussian beam (M^2=1, BBP = λ / π)



for Gaussian ('ideal') beam

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

for non-ideal beam an M2 factor introduced

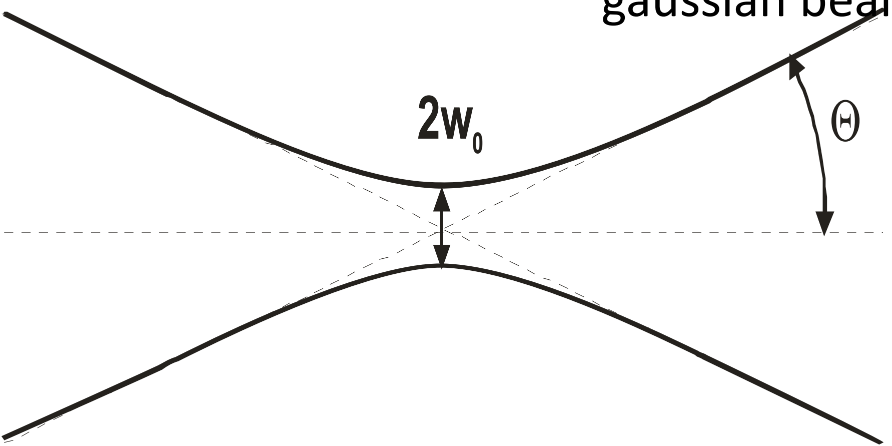
BPP (beam parameter product)

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

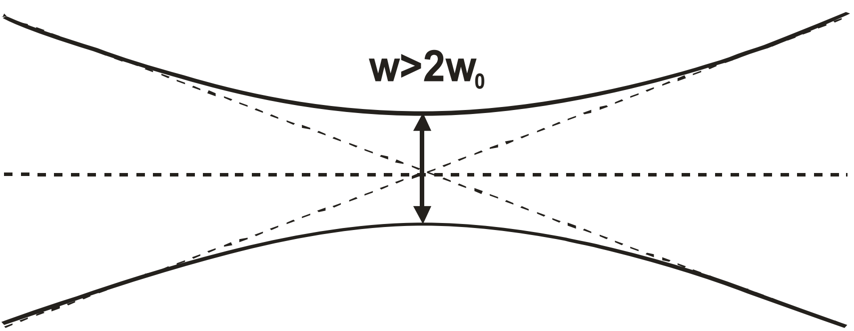
M2 is a wavelength-independent measure of beam quality (comparison with Gaussian beam)

M^2 Factor

gaussian beam (M^2=1, BBP = λ / π)

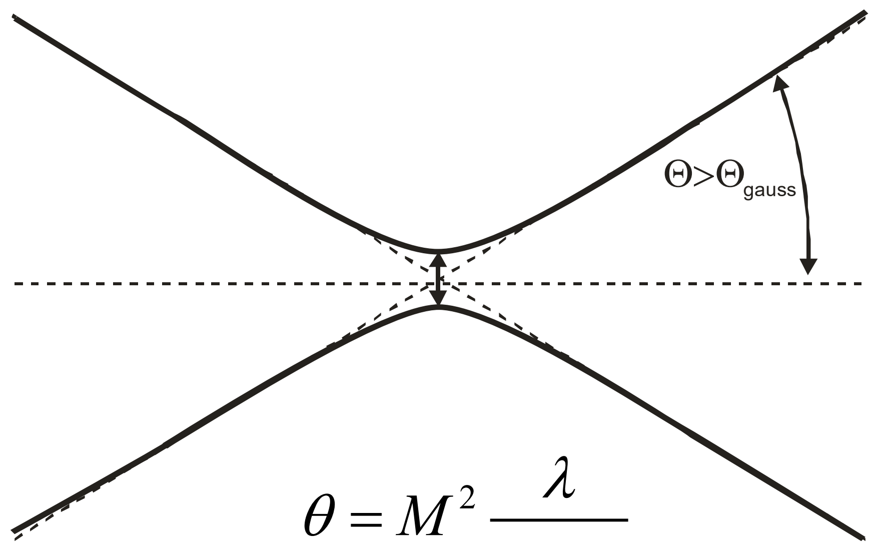


worse quality beam:
same focusing, larger spot



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

worse quality beam:
stronger focusing to get same spot



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

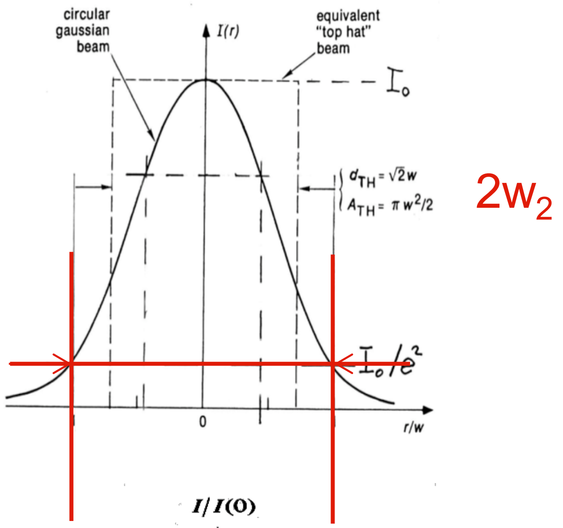
Comparison of Gaussian Beam and Plane Wave

Gaussian Beam

$$2w_2 \cong \frac{1}{2w_1}\frac{4\lambda f}{\pi} = \frac{1}{2w_1}1.27\lambda f$$

$$d_{G,FWHM} = \frac{1}{2w_1}1.18\lambda f$$

smaller spot!

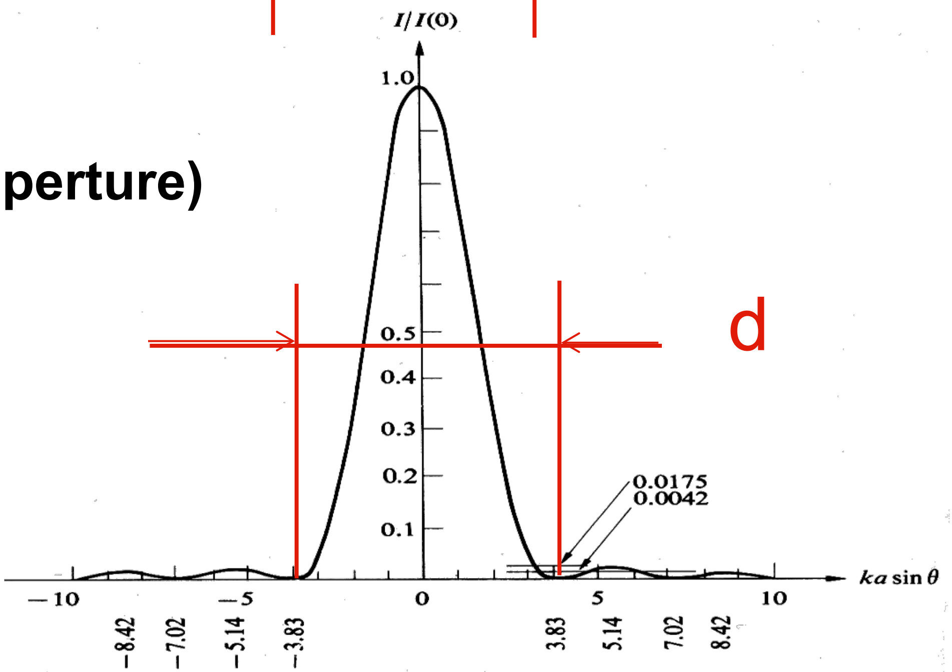


Airy (plain wave with circular aperture)

$$d \cong \frac{1}{D}2.44\lambda f$$

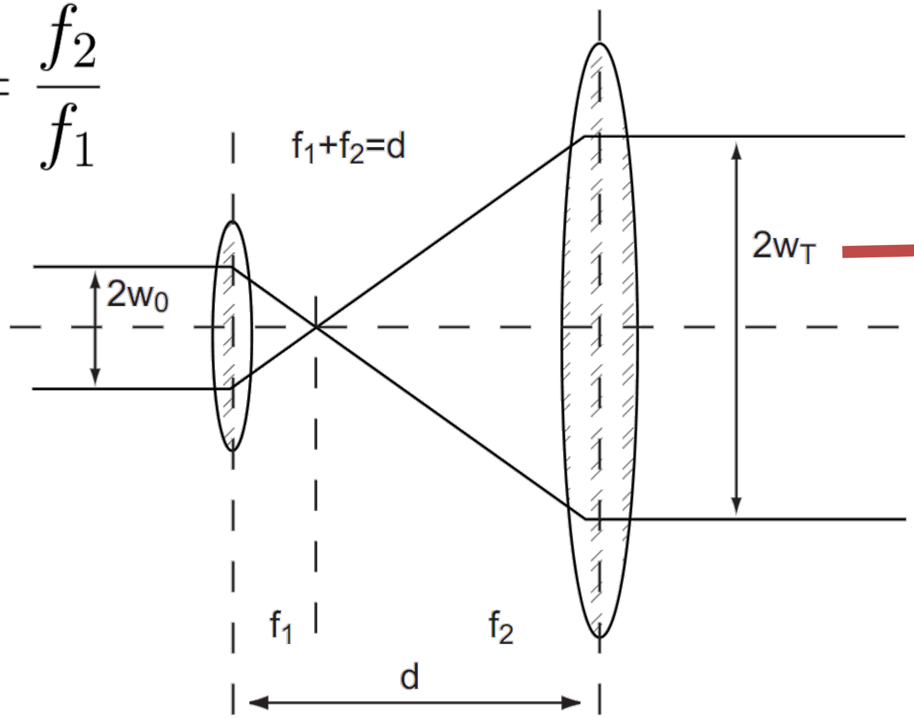
$$d_{Airy,FWHM} = \frac{1}{D}2.0\lambda f$$

larger spot!



Focusing

$$\frac{w_T}{w_0} = \frac{f_2}{f_1}$$



$$w_0 \approx \frac{2 f \lambda}{\pi a}$$

Telescope can be used to increase beam diameter
$\Rightarrow$ and reduce the minimal spot size

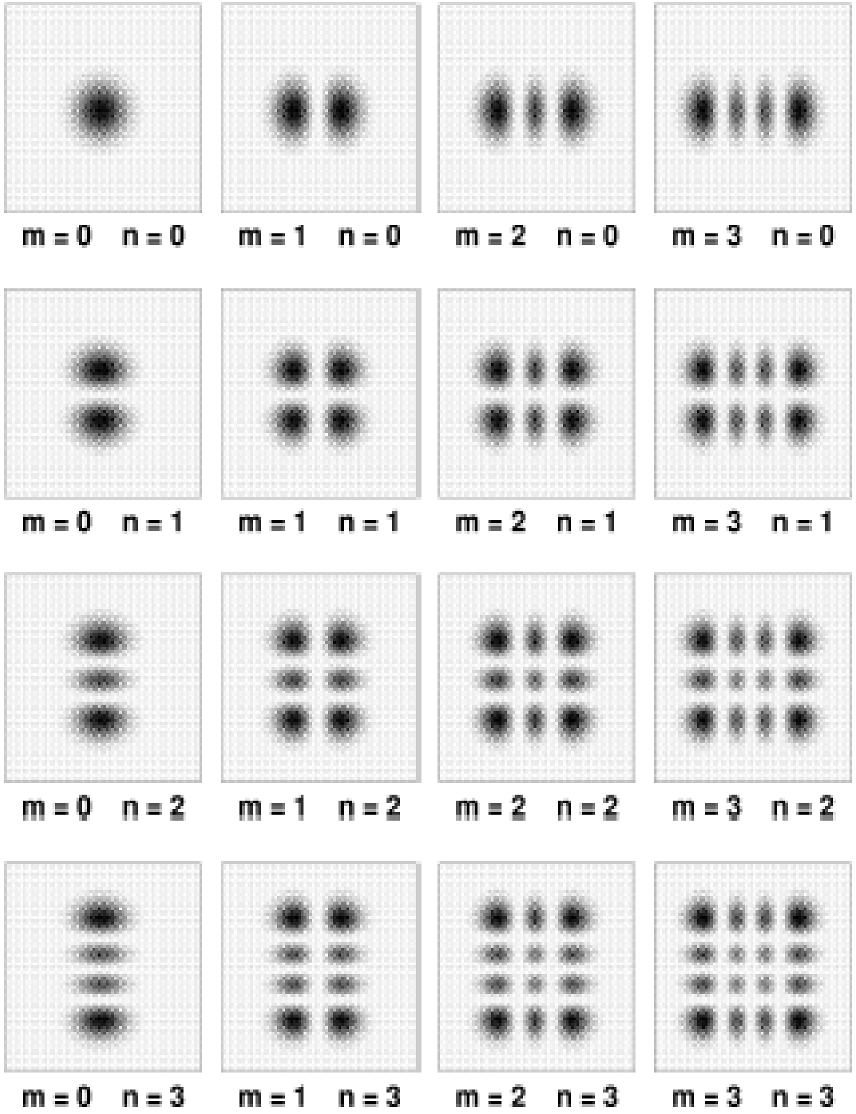
Why Beam is not always Gaussian?

Modes TEM $_{m,n}$

Beam quality, M^2: The ratio of the laser beam's multimode diameter-divergence product to the ideal diffraction limited (TEM_{00}) beam diameter-divergence product

$M^2=1$ → Gaussian beam

$q^*=M^2 \cdot \lambda/\pi$



Gauss-Laguerre modes

(Helmholtz equation solutions in cylindrical coordinnates)

$$U_{p,\ell}(r,\varphi,z) = \overbrace{U_0\left(\sqrt{2}\,\frac{r}{w(z)}\right)^{\ell}}^{A}$$

$$\cdot \overbrace{L_p^{(\ell)}\left(2\left(\frac{r}{w(z)}\right)^2\right)\cdot\begin{pmatrix}\cos(\ell\varphi)\\ \sin(\ell\varphi)\end{pmatrix}}^{B}$$

$$\underbrace{\cdot\exp\left(-\frac{r^2}{w^2(z)}\right)}_{C}\underbrace{\cdot\exp\left(-i(2p+\ell)\cdot arc\tan\left(\frac{z}{z_0}\right)\right)}_{D}$$

<u>Termes:</u>

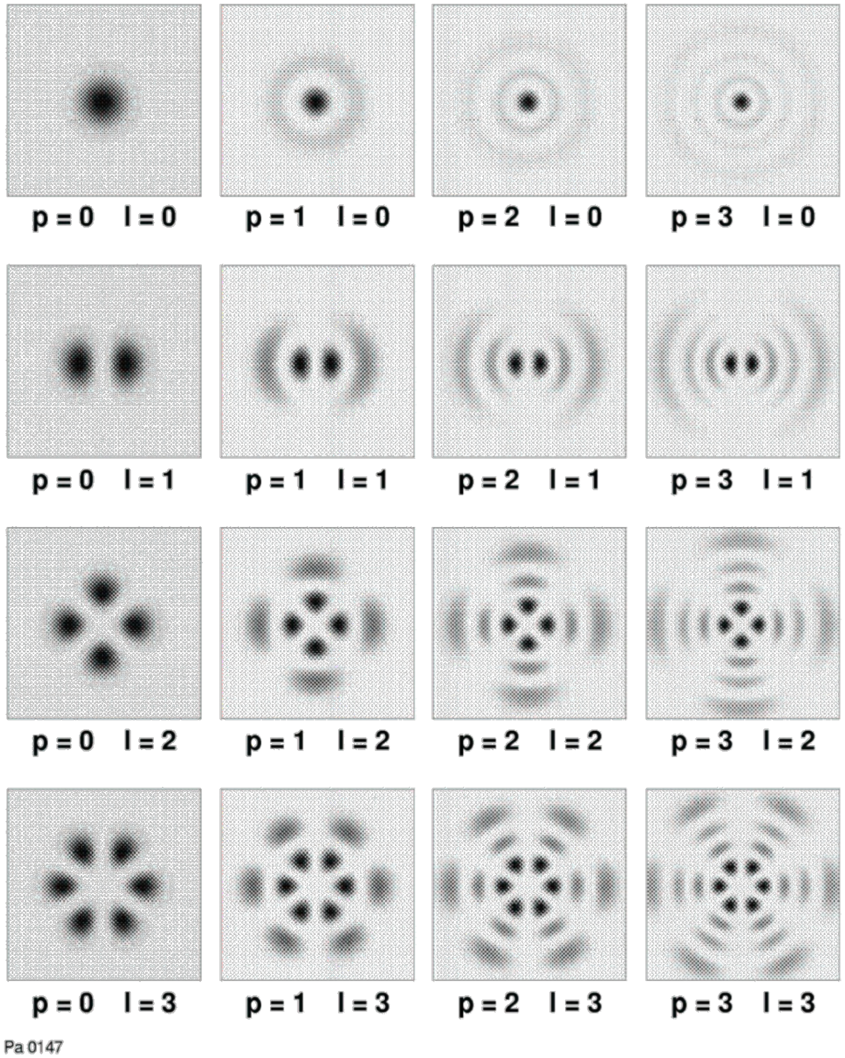
A: Amplitude; B: Hermite functions;

C: Gauss functions ; D: Phase

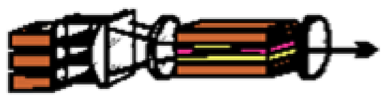
Polynôme de Laguerre:

$L_0^{(0)}(\rho)=1;\quad L_1^{(0)}(\rho)=1-\rho;$

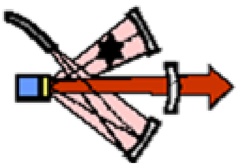
$L_2^{(0)}(\rho)=1-\frac{\rho 2}{2};\qquad \rho=\frac{\sqrt{2}r}{w(z)}$



Comparison of BBP for Different Laser Designs

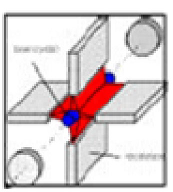


INNOSLAB

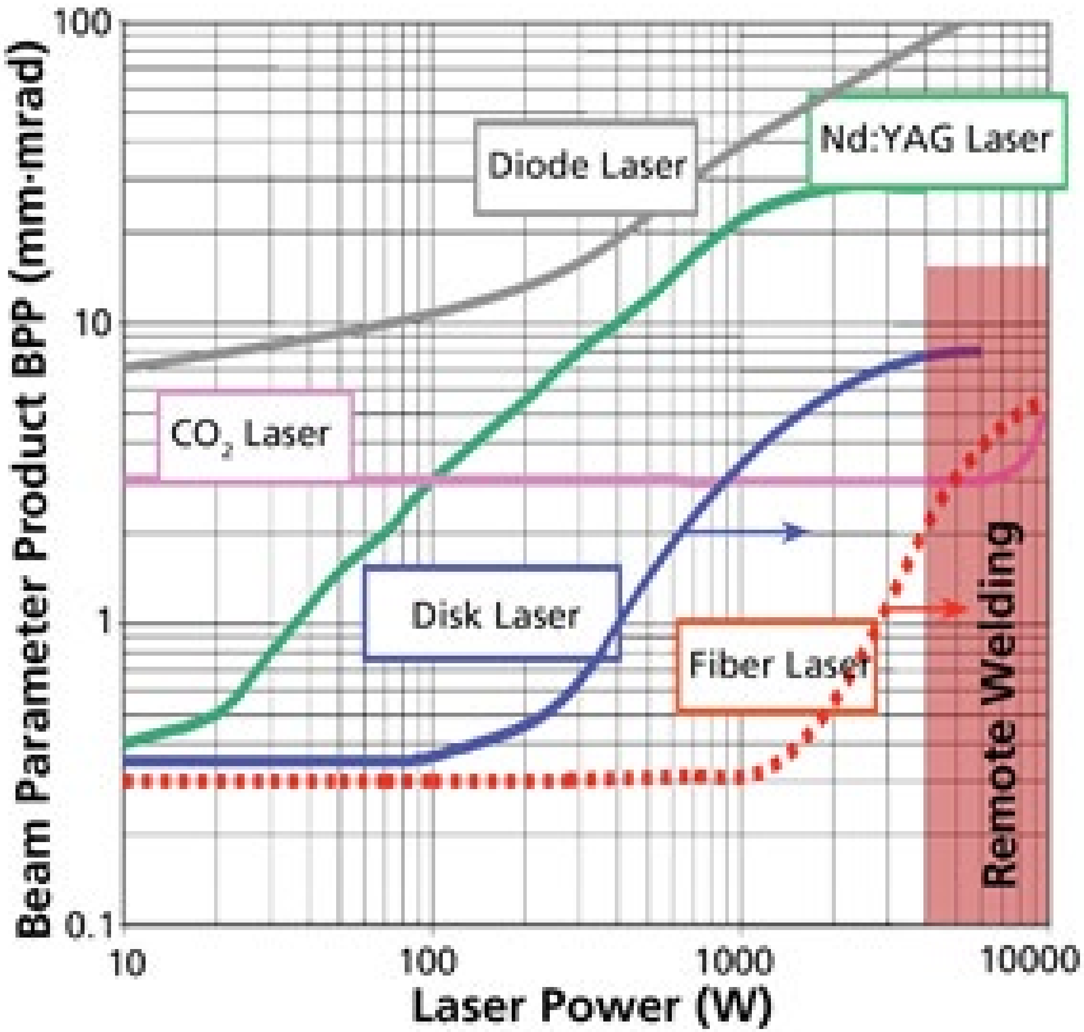


Thin Disk Laser

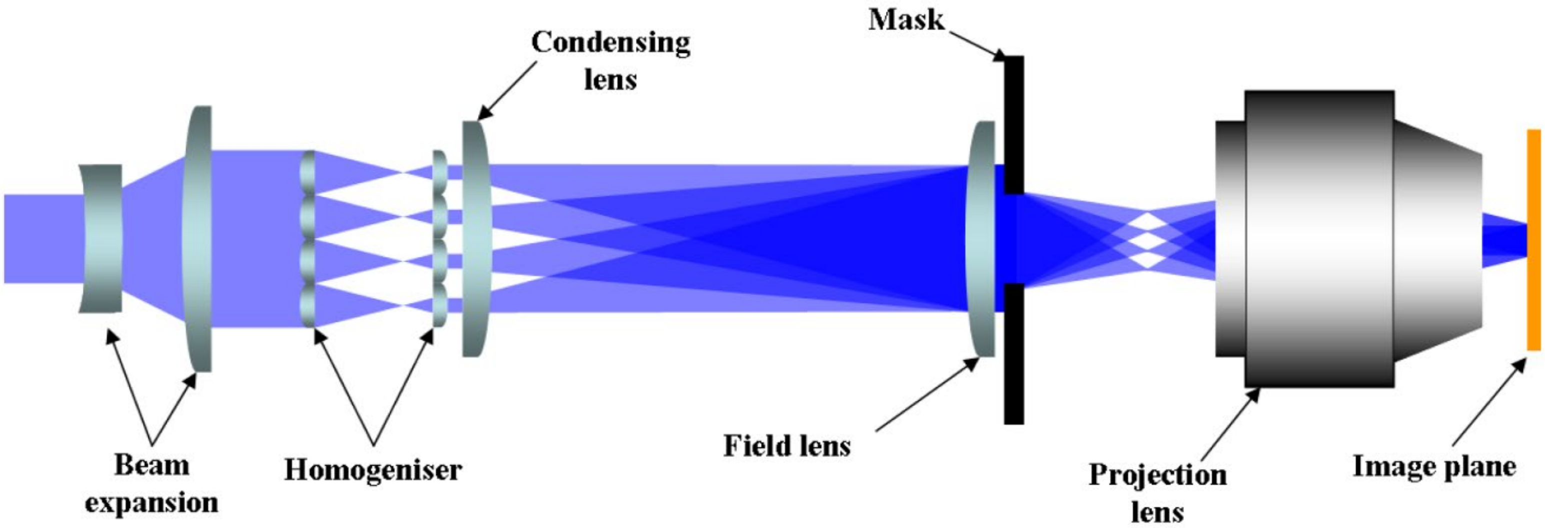
Fiber Laser

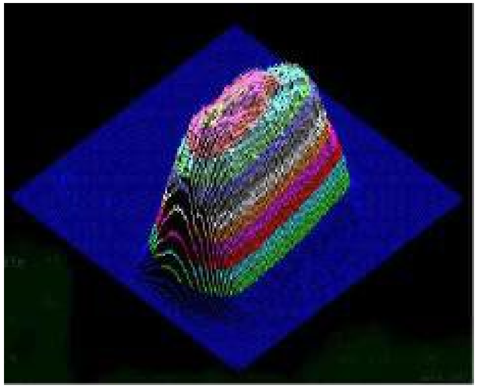


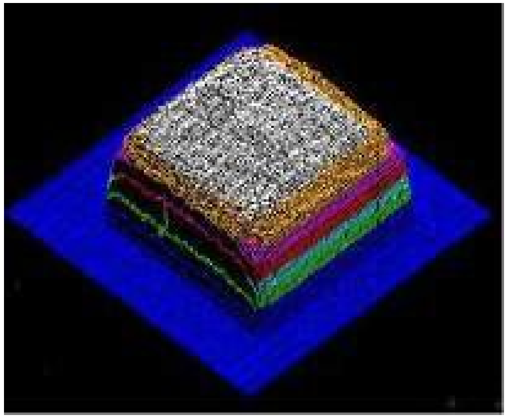
Rod Laser



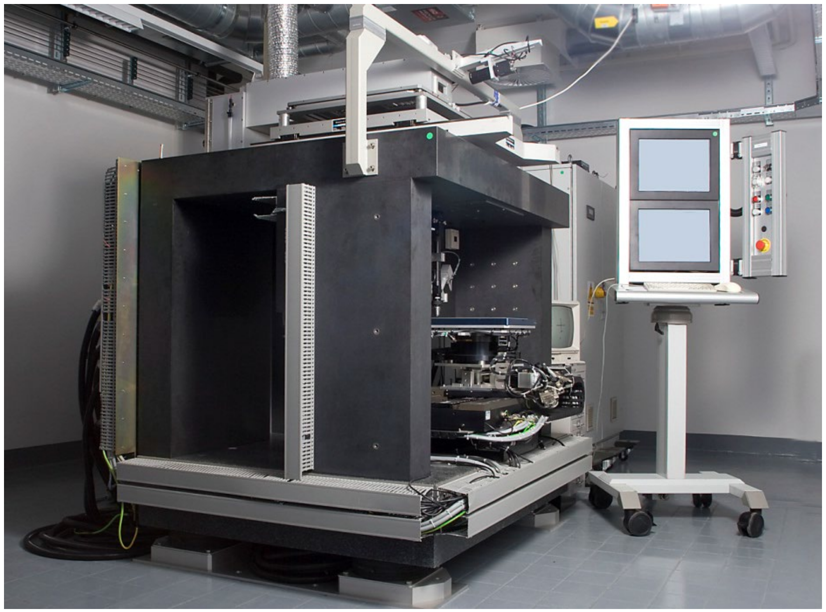
Mask projection system

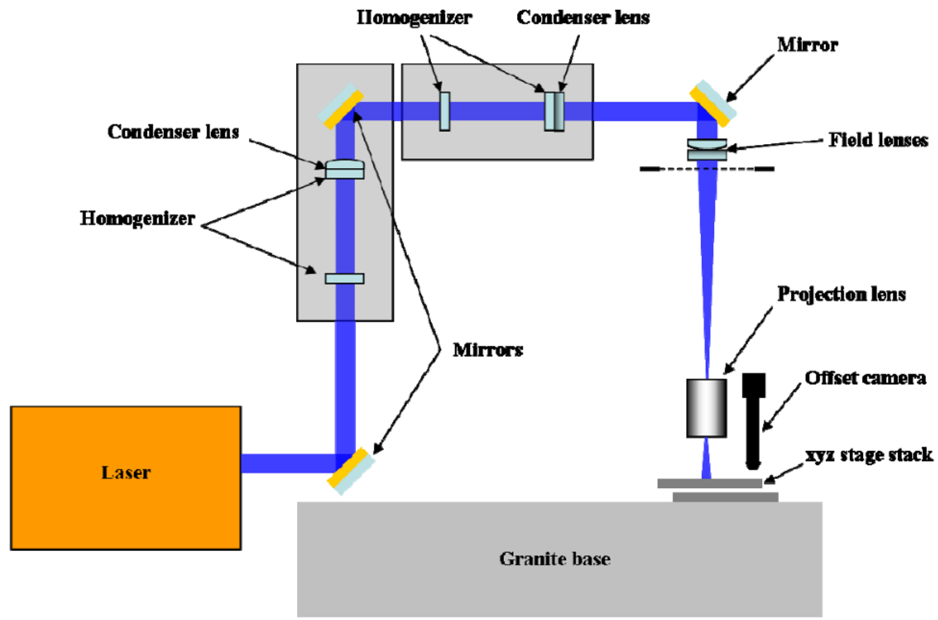






Exitech M8000 Micromachining System





Travel	400 mm
Accuracy	±0.50 µm
Repeatability	±0.20 µm
Straightness	±0.40µm
Flatness	±0.40µm

CREALAS
Smart Micromachining

Method Based on Interference