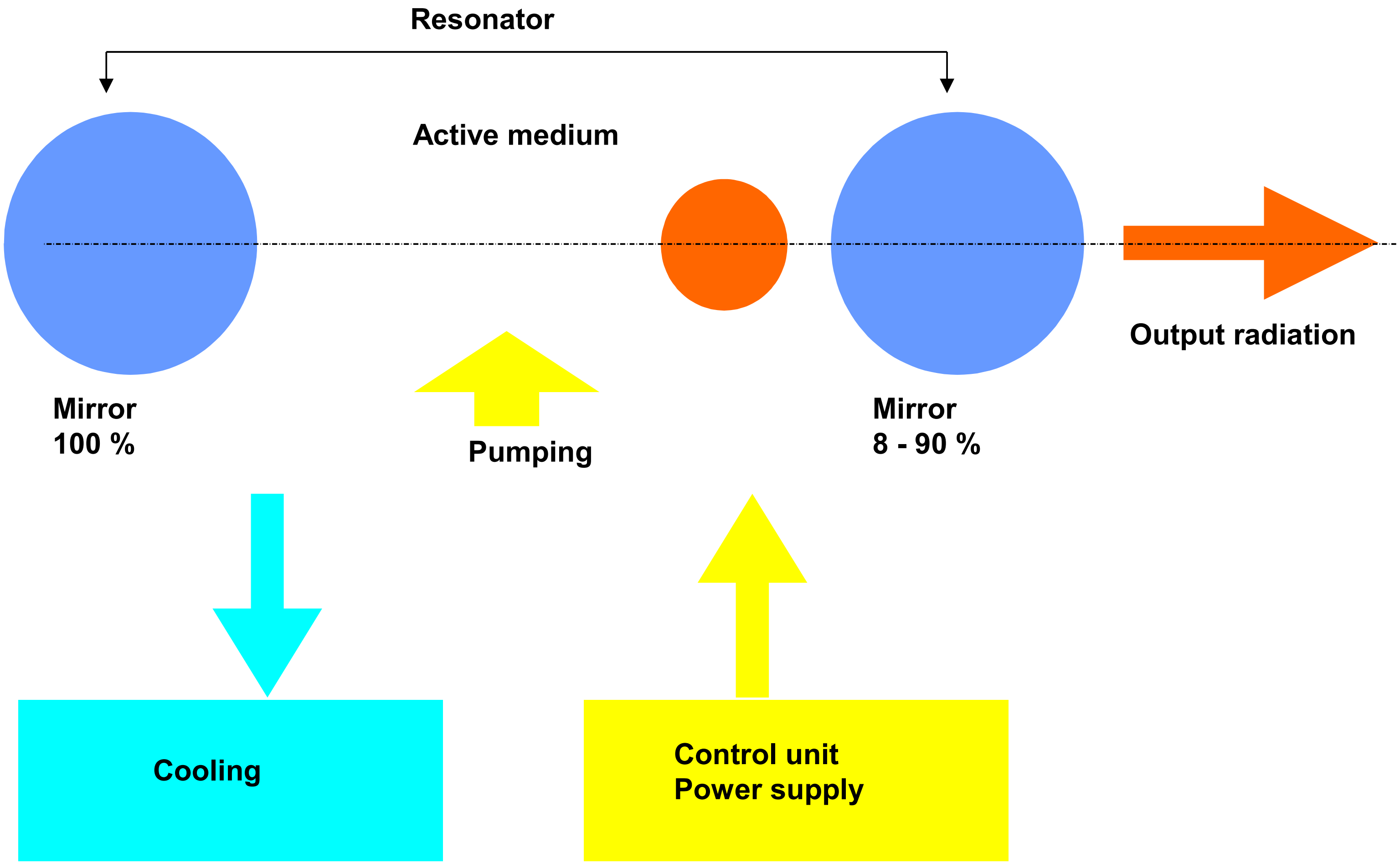
Lasers - instrumentation

Vítězslav Otruba

Less common prefixes

prefix	symbol	exponent
atto	a	10-18
femto	f	10-15
piko	p	10-12
nano	n	10-9
giga	G	109
tera	T	1012
peta	P	1015
exa	E	1018

Solid-state laser



Resonator

Active medium

Output radiation

Mirror
100 %

Pumping

Mirror
8 - 90 %

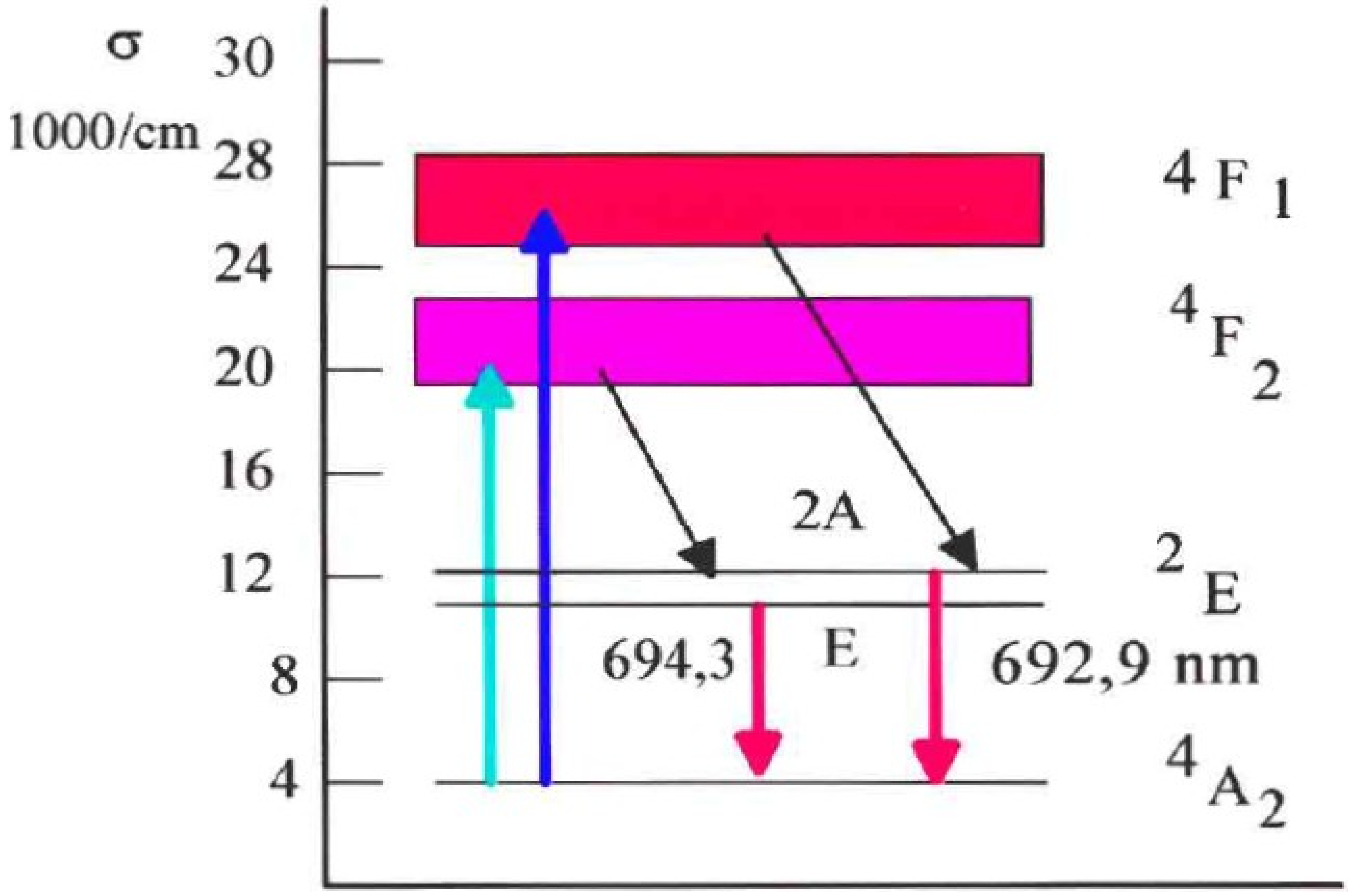
Cooling

Control unit
Power supply

Ruby laser ($Cr^{3+}:Al_2O_3$)

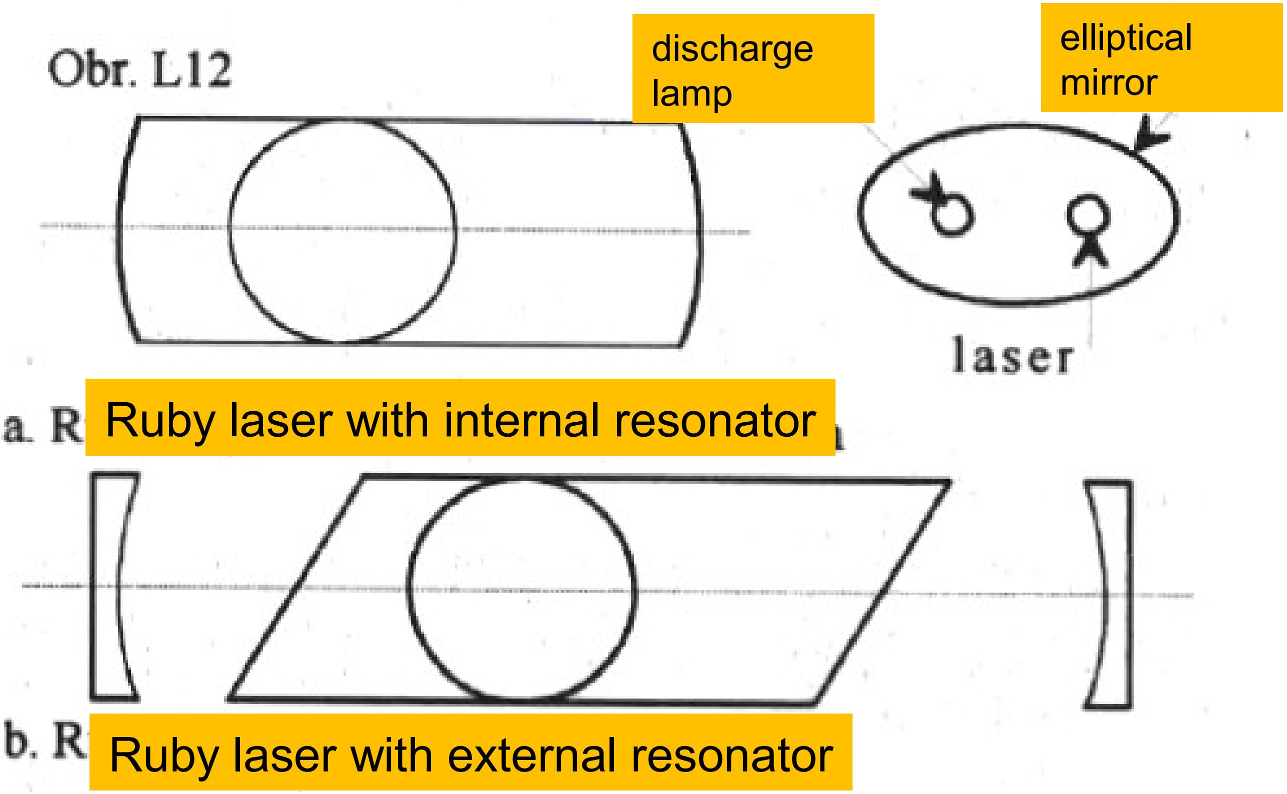
- The first laser designed by T. Maiman in 1960.
- Used in pulse mode, power in free running mode to 10J (1ms),
- in Q-switched mode to 5J (1 – 10 ns)
- three-level system

diagram of chromium energy levels in ruby laser



ruby laser

- arrangement of ruby laser

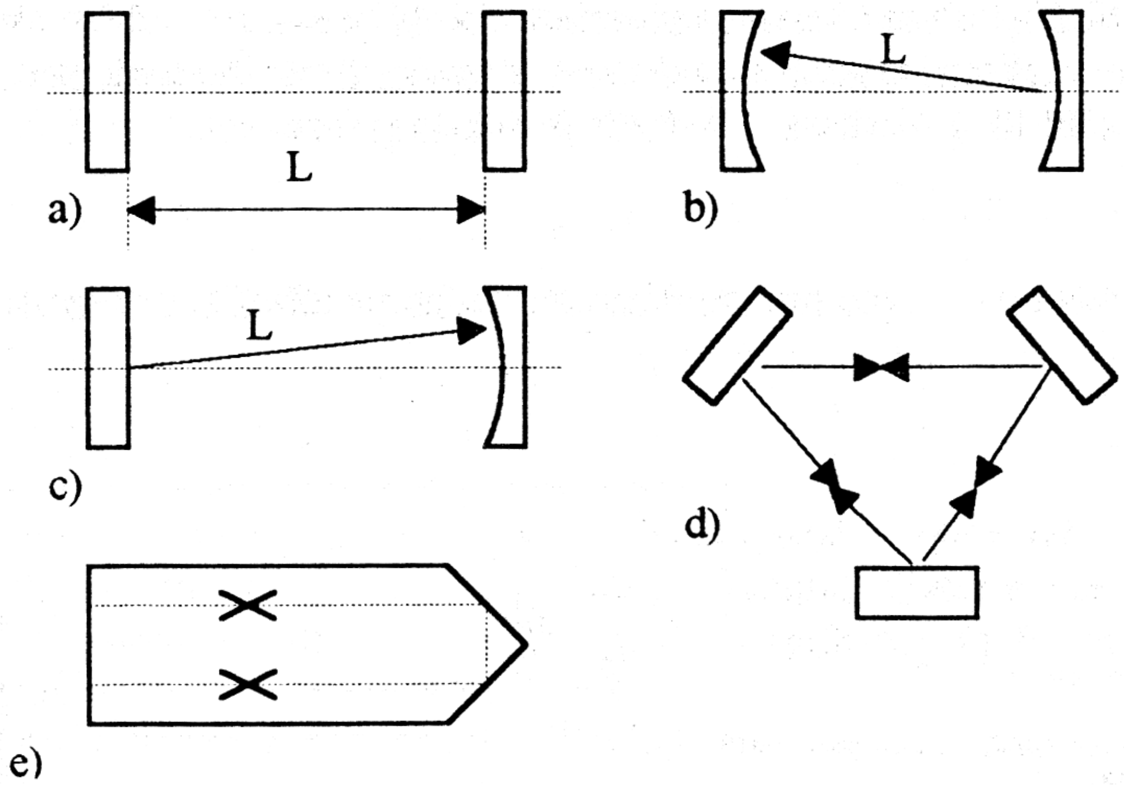


Ruby laser with internal resonator

Ruby laser with external resonator

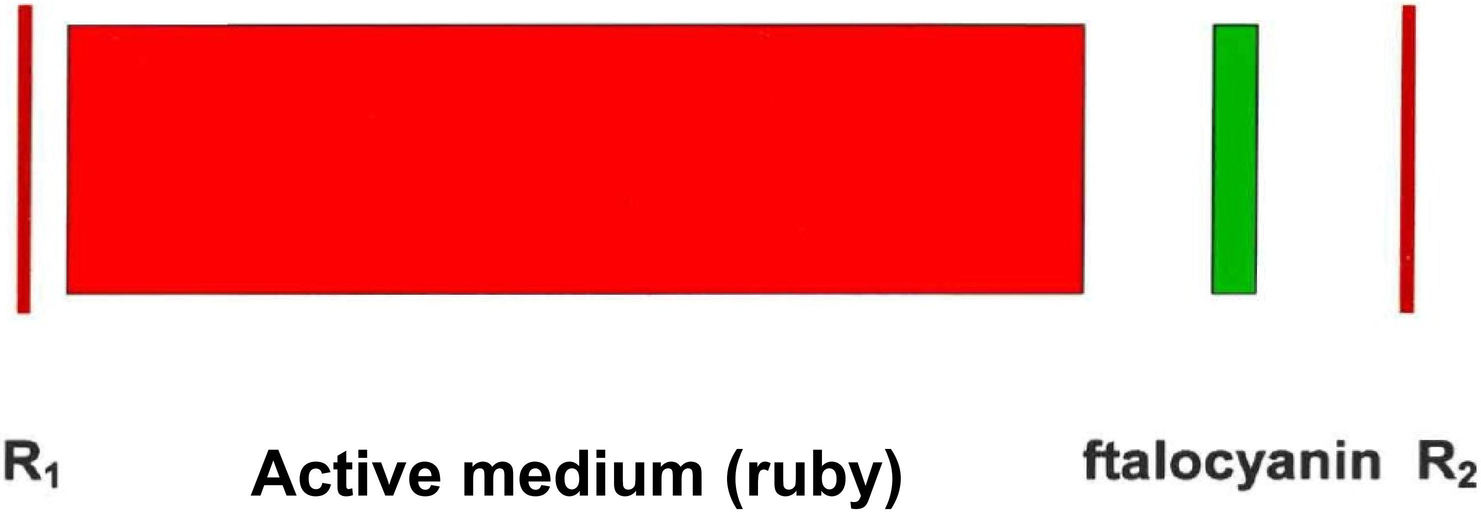
Resonators

- Fabry-Perot etalon
- plan parallel
- confocal
- hemispherical
- circular
- roof



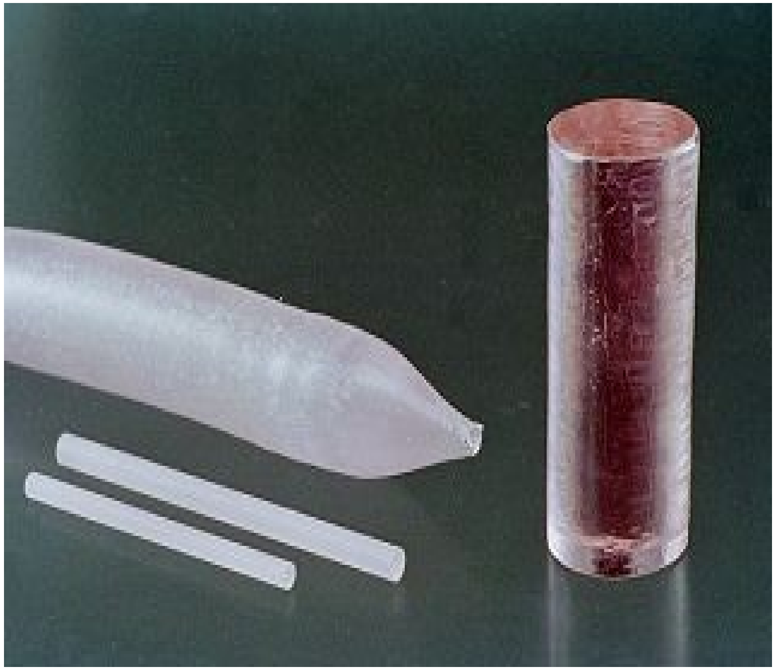
Passive Q-modulation

- Example of use of saturation absorber for generation of short (nanosecond) power pulses (GW) in ruby laser



Neodymium laser

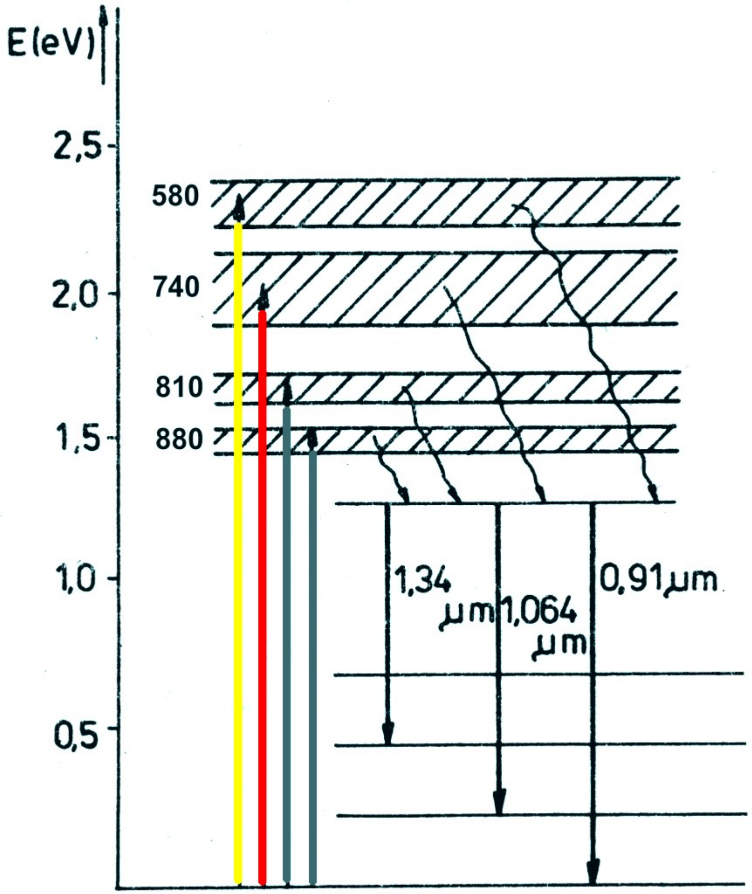
- It is the most widespread solid state laser(cca 1% Nd v $Y_3Al_5O_{12}$) . It operates at 1,064 nm, in continuous mode power to 1 kW,



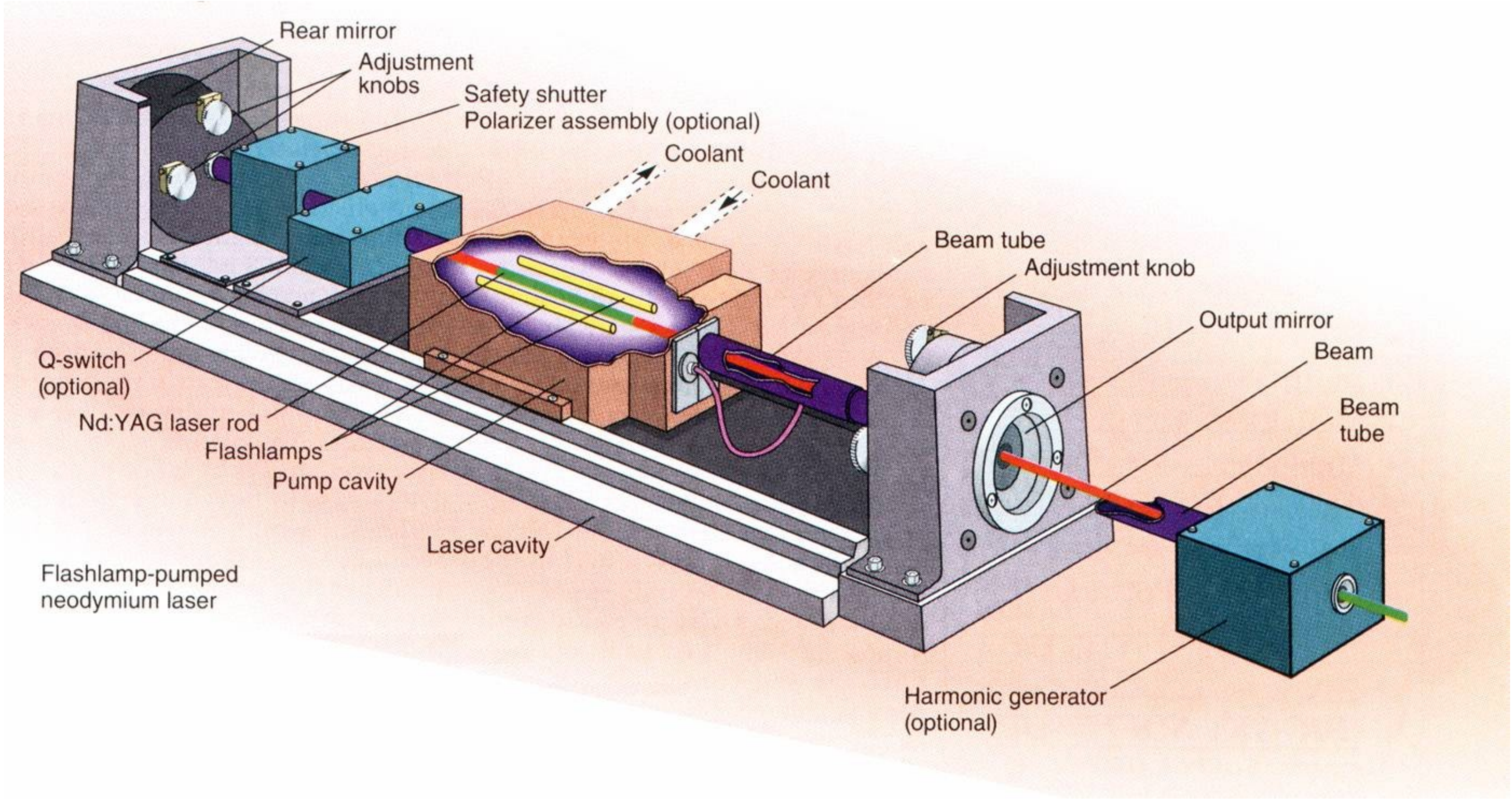
- pulse to 10 J, repetition rate up to kHz. In Q-switched pulse mode 1 – 10 ns,
- at synchronizing modes to 10 ps.

Neodymium energy level diagram of Nd in: YAG laser

- Nd3+ in yttrium-aluminum garnet (Y3Al5O12) replaces ions Y3+. Monocrystals are mechanically strong, thermally stable with minimal optical defects unlike neodymium glasses. Xenon lamps or laser or LED diodes are used for pumping.

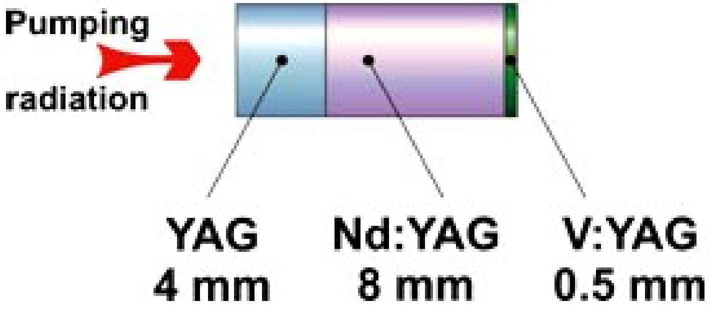


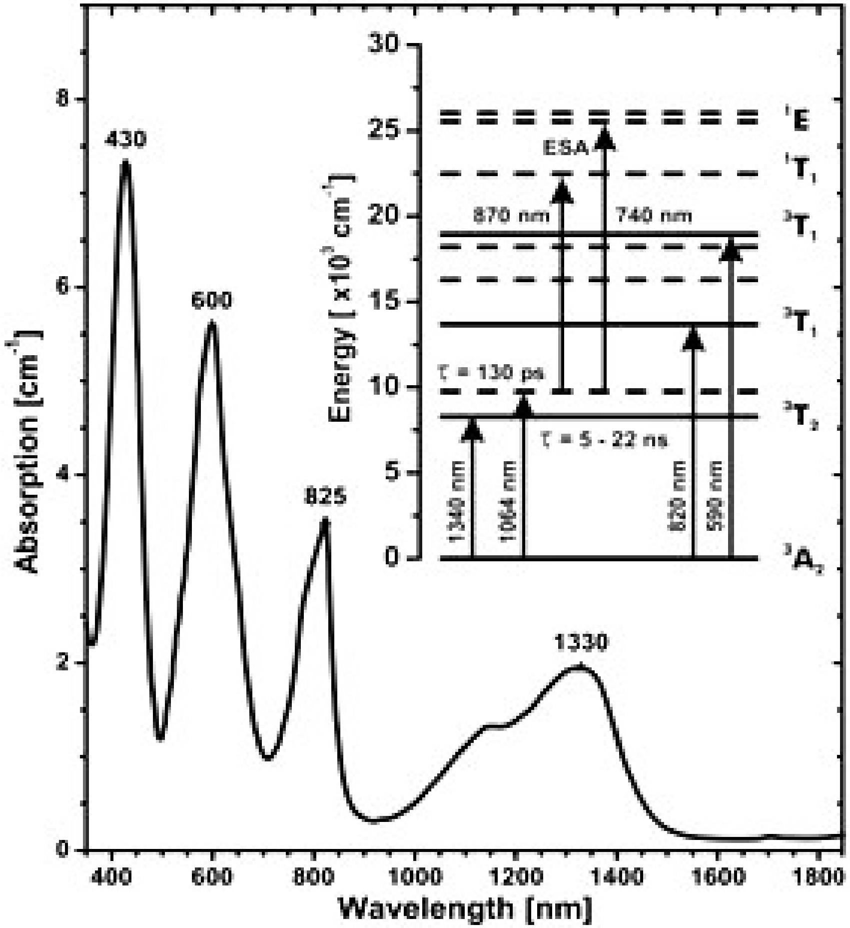
Neodymium laser



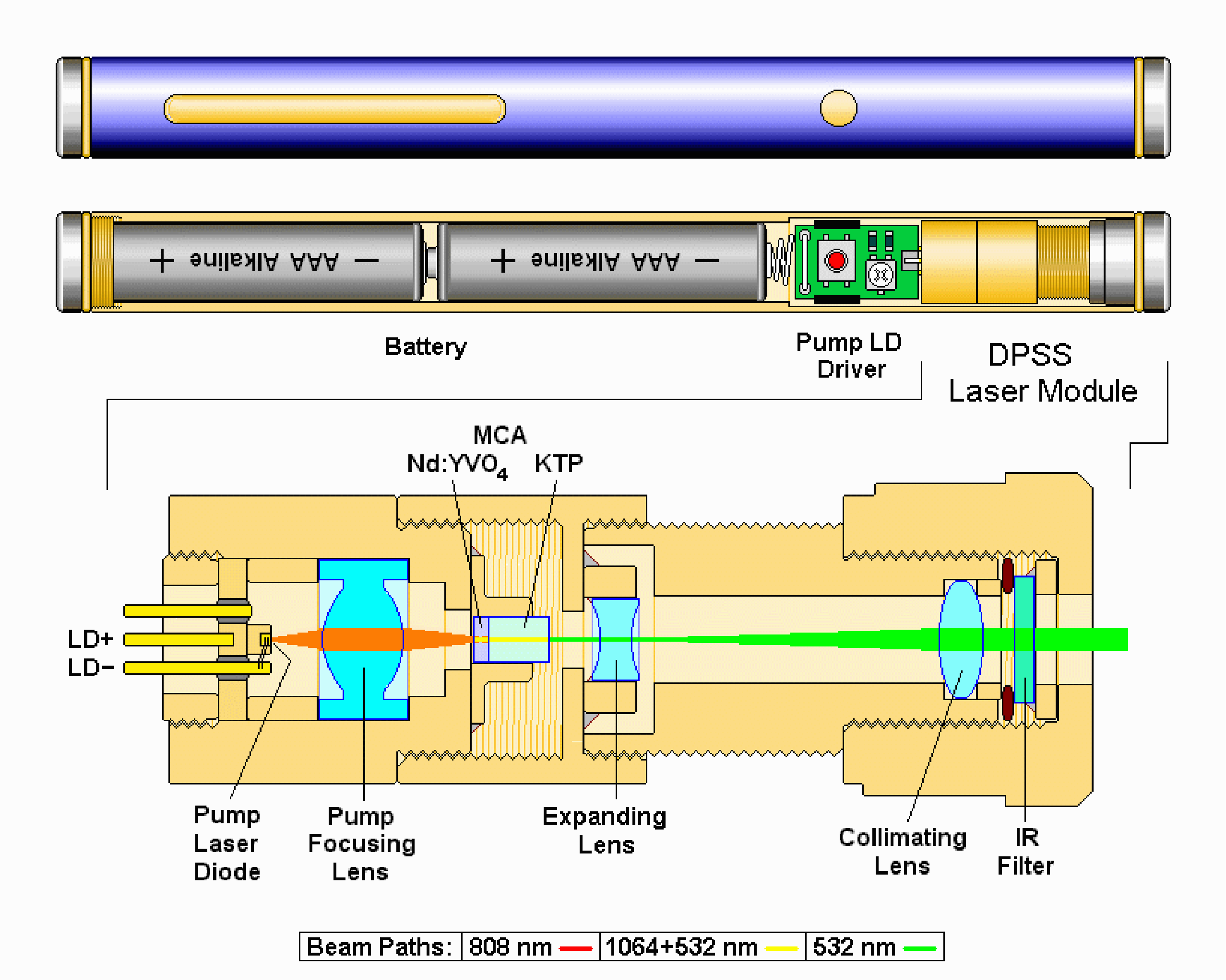
Flashlamp-pumped neodymium laser

Passive Q-modulation V3+:YAG

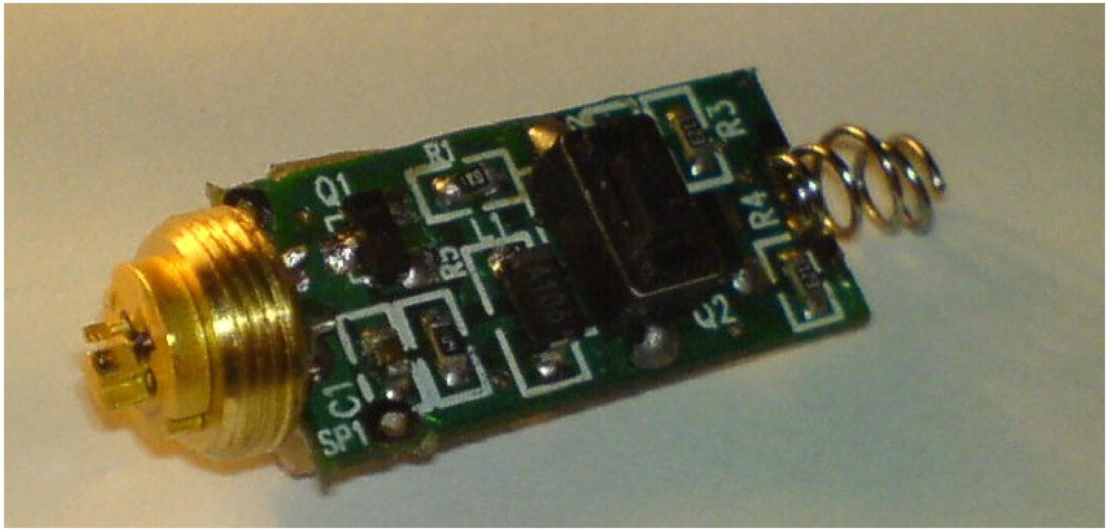


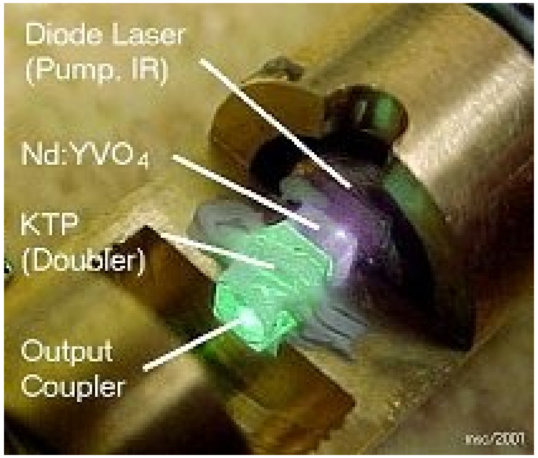


Green laser pointer



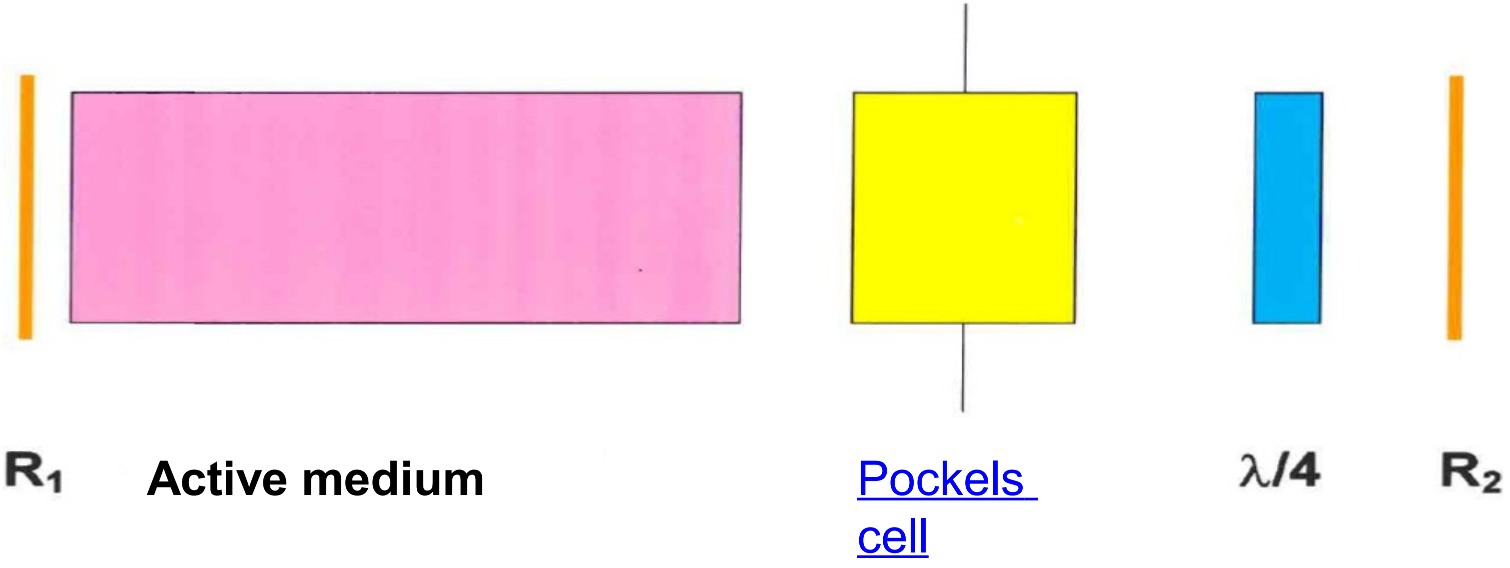
Green laser pointer





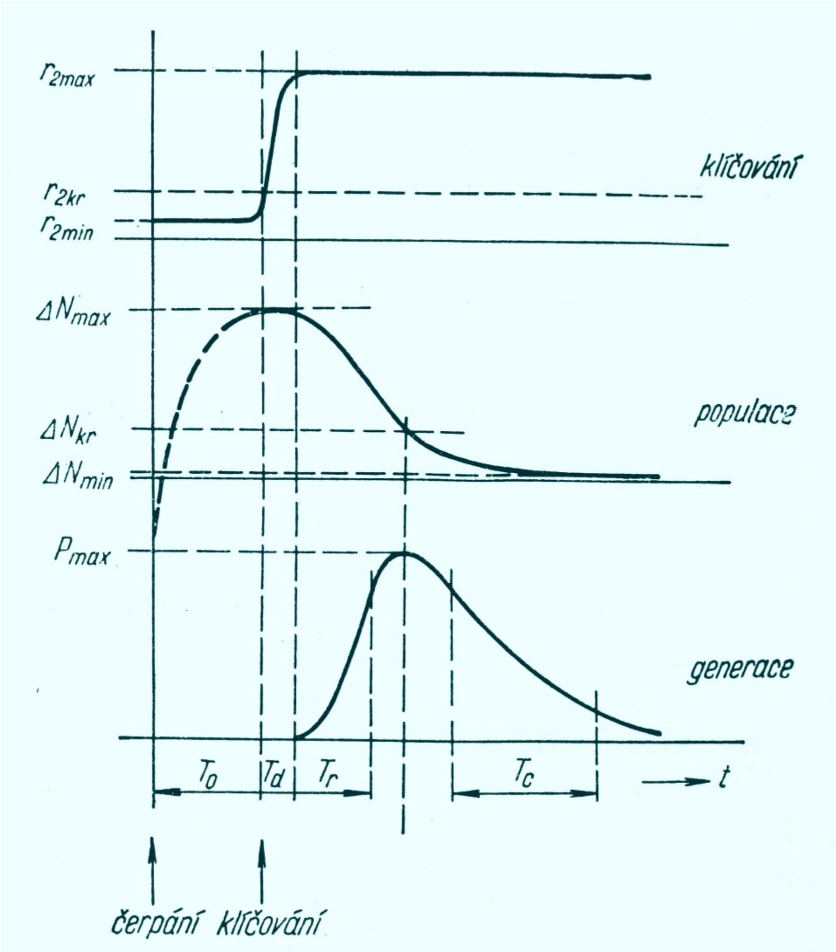
Active Q-modulation

- In this case, the Q of resonator is modulated by optical shutters, such as a Kerr effect electro-optical modulator or an acoustooptical module.



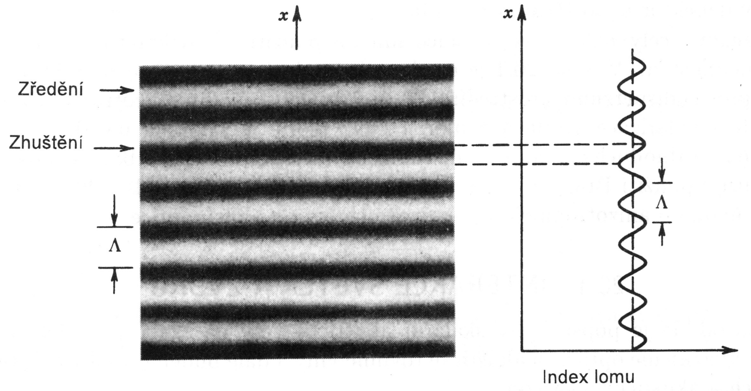
Timing of active Q-modulation

- Typical timing for Nd:YAG laser:
- Inverse population increase (T0) 150μs
- Trigger pulse (TD) 1 ns
- Generation of radiation 10ns

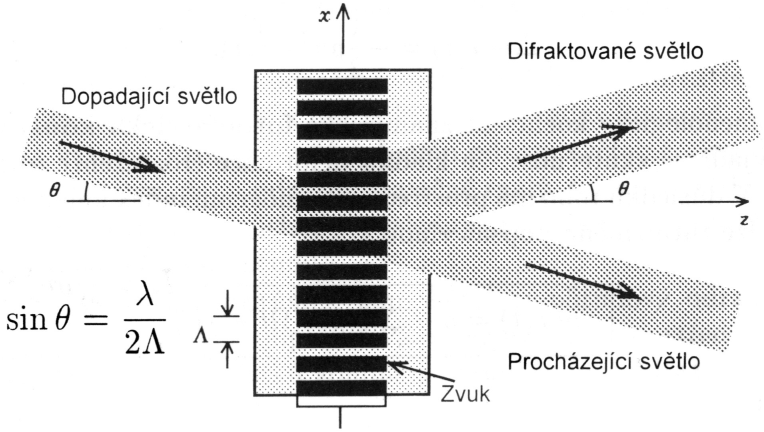


Optoacoustic modulator

- If the sound propagates through the optical environment, the density and thus the refractive index change.

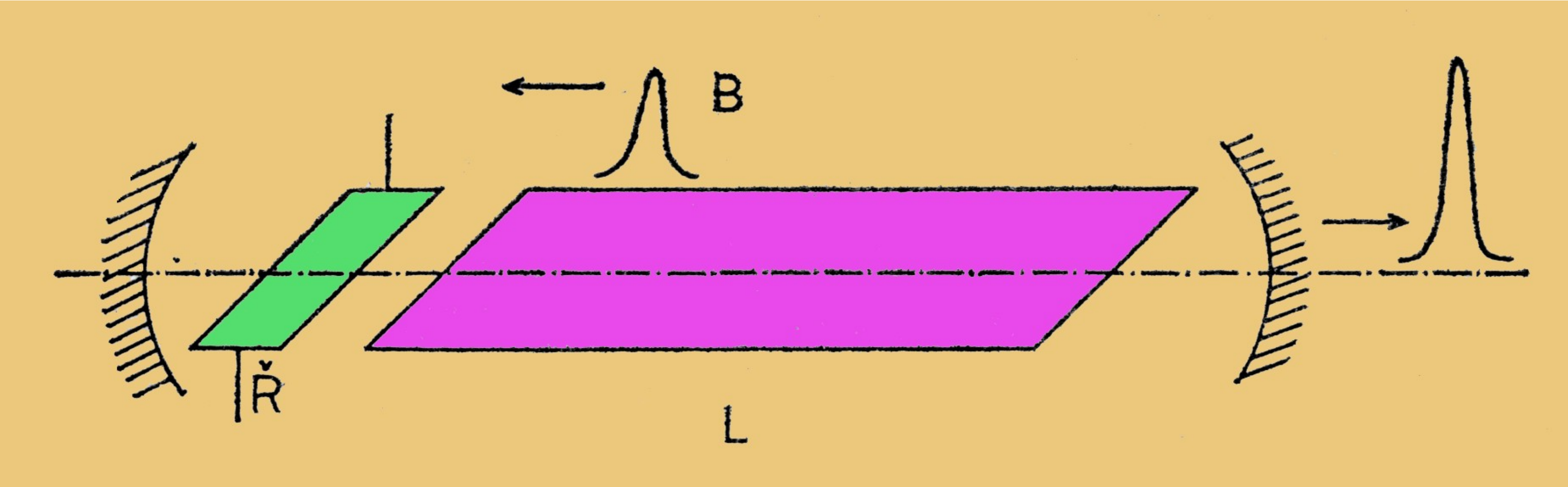


- The simplest is the Bragg diffraction: the acoustic plane wave causes a partial reflection of the radiation if the angle Θ satisfies the Bragg condition (Bragg cell)



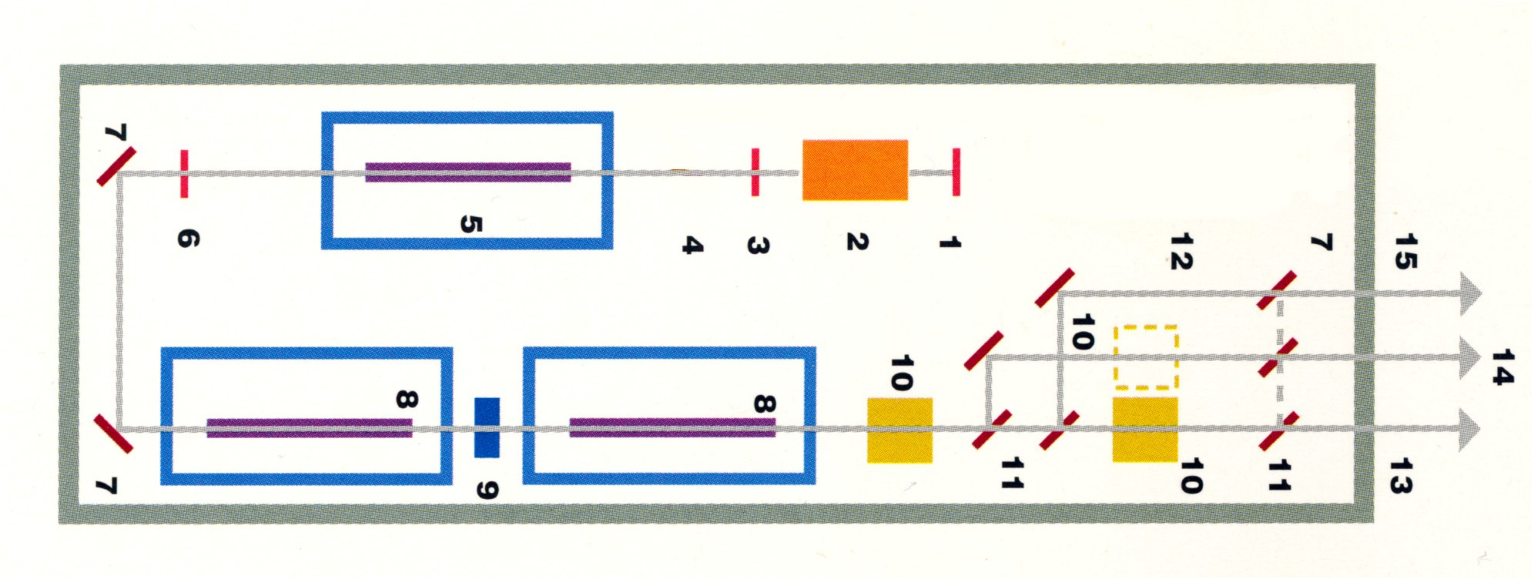
Mode-locking

- Passive or active modulation of the resonator with frequencies f = c / 2L gives a sequence of very short pulses, the length of which is determined by the Fourier transform of the spectral line and the repetition rate by the time the photon cloud travels back and forth.

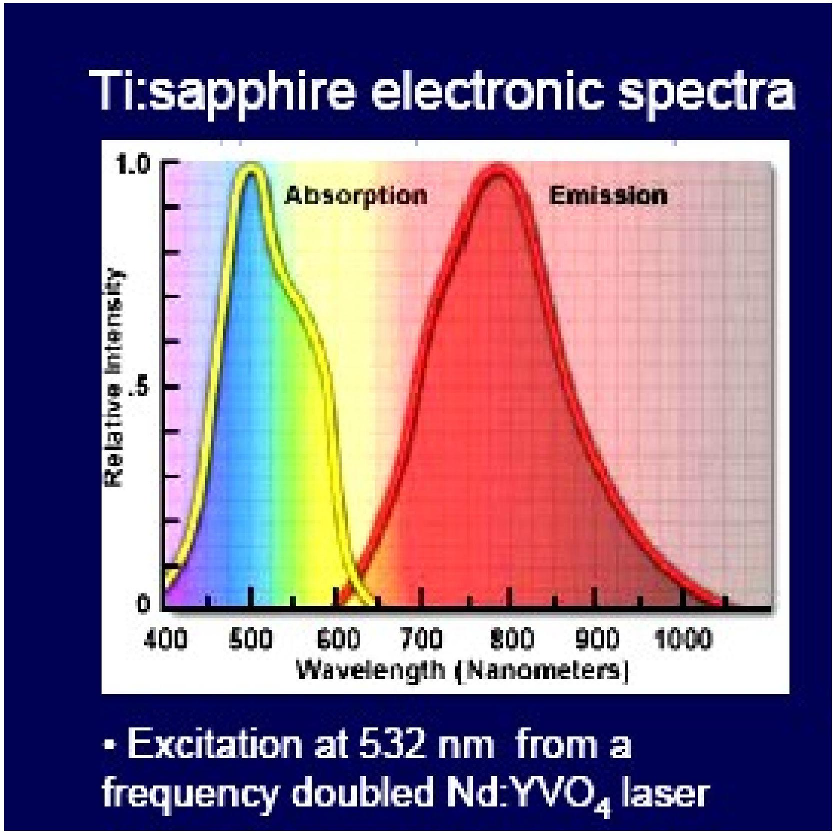


Nd:YAG laser

- Laser with Q-modulation (1-6), two-stage amplifier (8), birefringence compensator (9) and harmonic frequency generators (10), output 1064 nm (13), 532/355 nm (14), 266/1064 nm residual (15)



Titanium Doped Sapphire Al2O3:Ti3+



Ti:sapphire electronic spectra

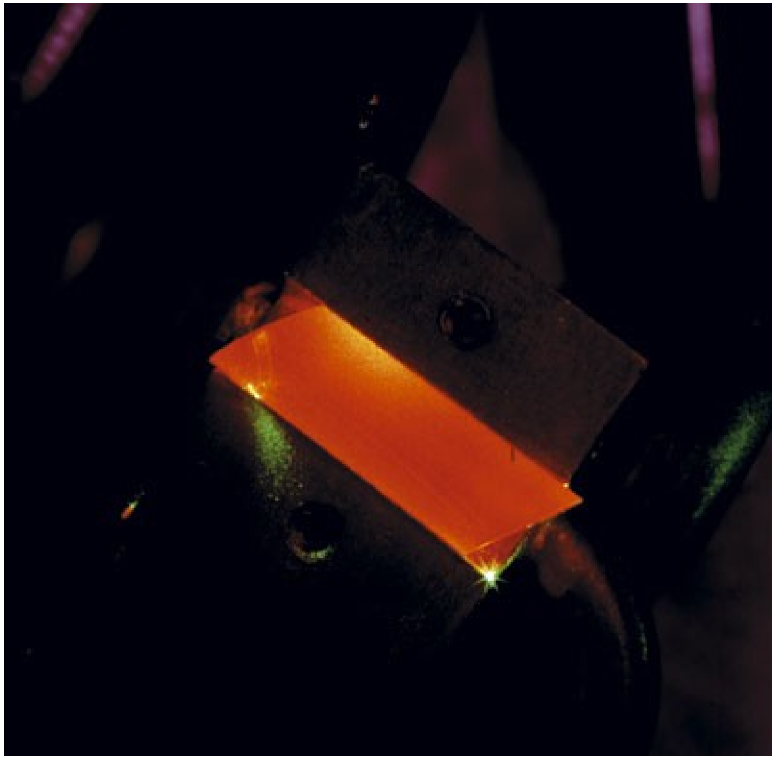
- Excitation at 532 nm from a frequency doubled Nd:YVO_4 laser

Titanium Doped Sapphire $Al_2O_3:Ti^{3+}$

- Ti_2O_3 concentration 0.06-0.5 wt%

  Hardness 9 Mohs

  Thermal conductivity 0.11 cal/ (°C x sec x cm)



- **Optical Properties**

  Laser action 4-Level Vibronic

  Fluorescence lifetime 3.2 *μ*sec (T = 300 K)

  Tuning range 660-1050 nm

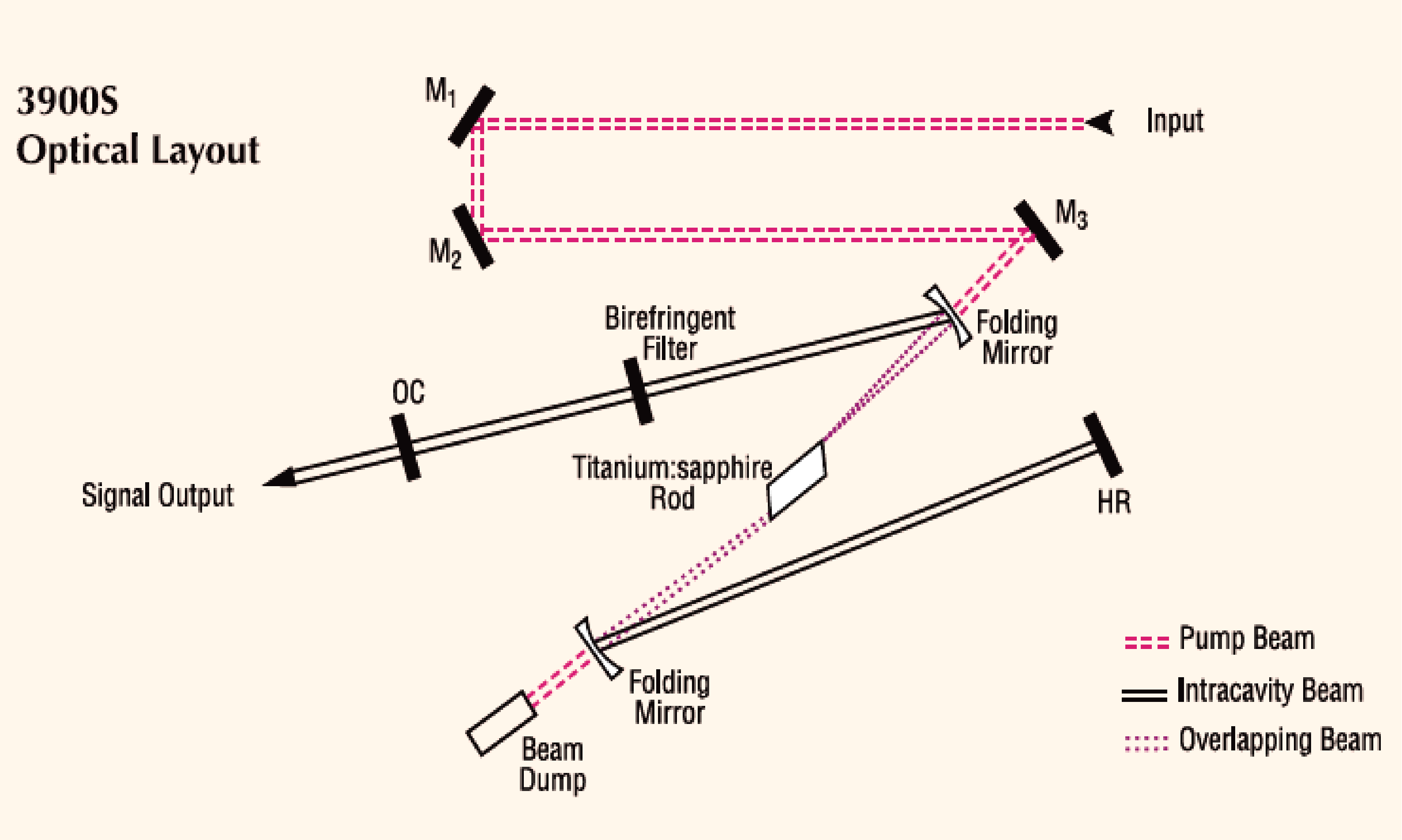
  Absorption range 400-600 nm

  Emission peak 795 nm

  Absorption peak 488 nm

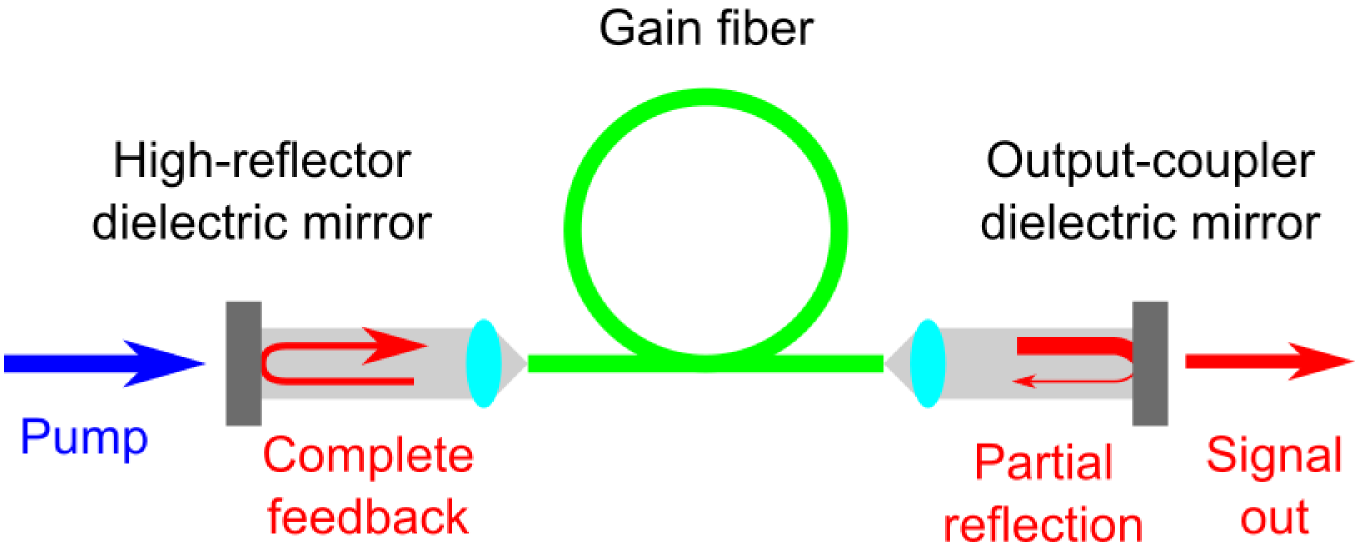
  Refractive index 1.76 @ 800 nm

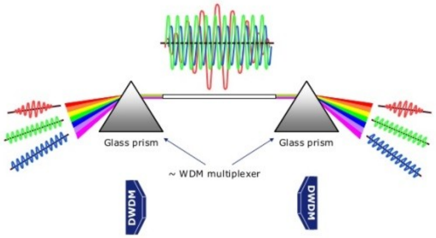
Titanium Sapphire Laser



Fiber lasers

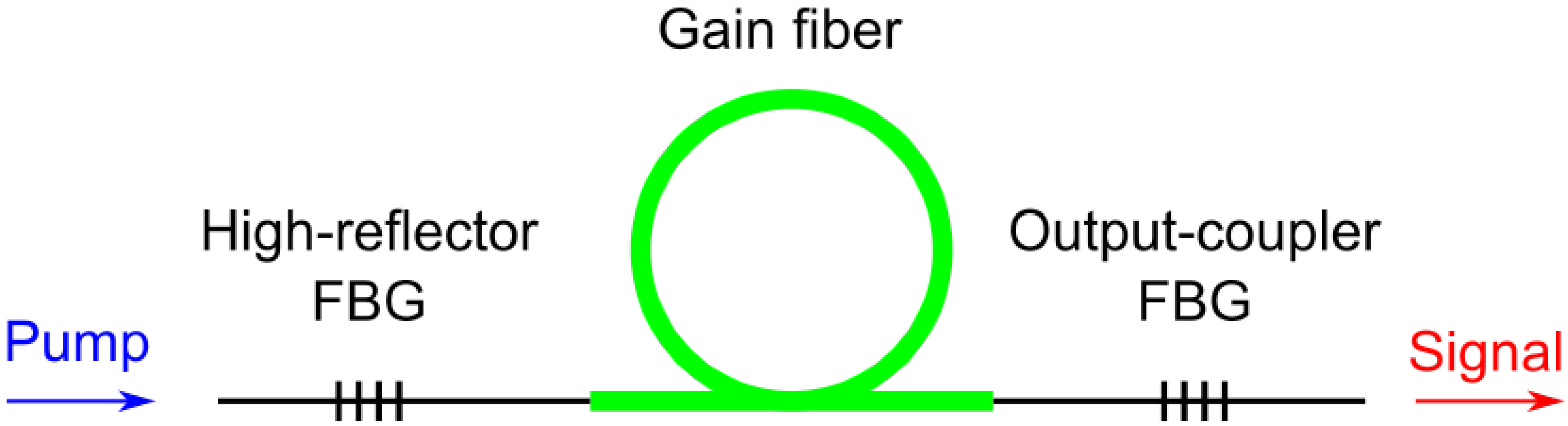
- Arrangement with Linear Fabry Perot Resonator
- *WDM* (Wavelength Division Multiplex)



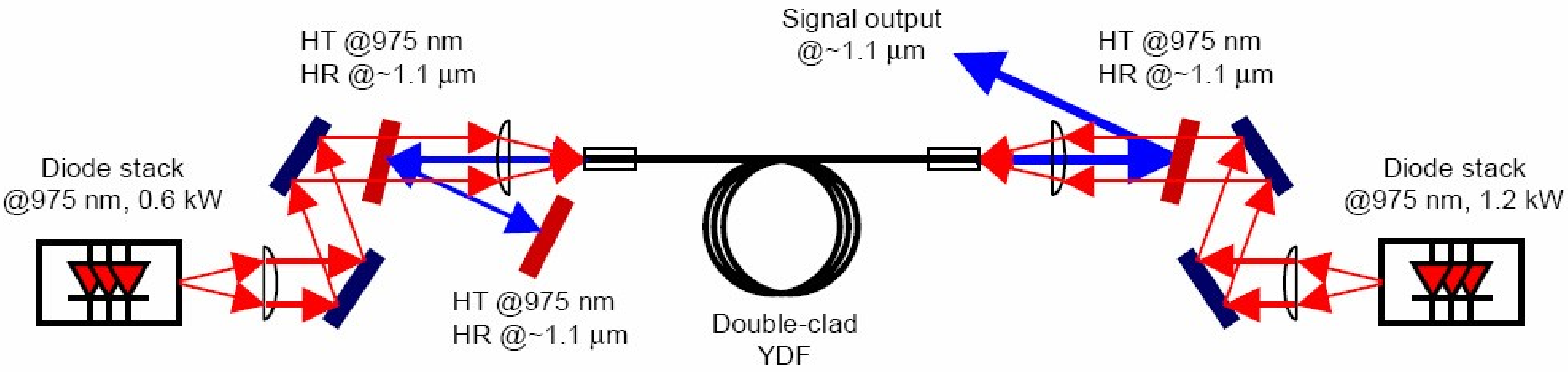


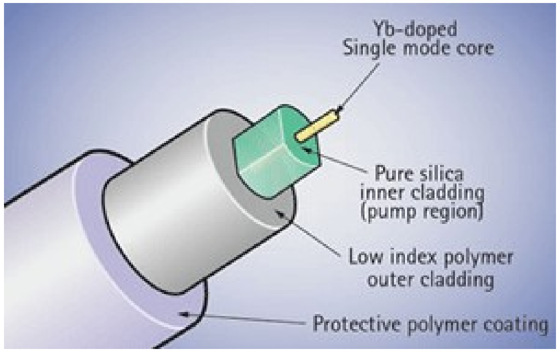
Fiber lasers

- FBG – Fiber Bragg Grating

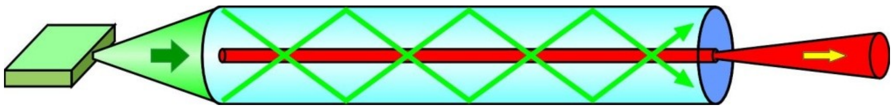


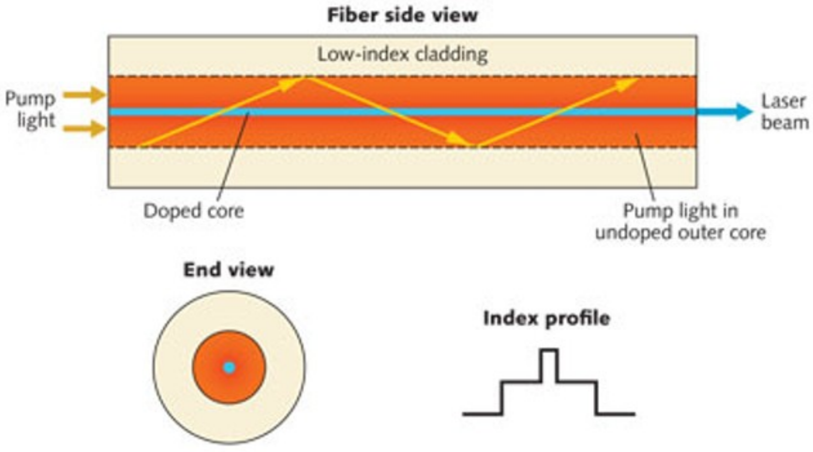
Ytterbium doped fiber laser

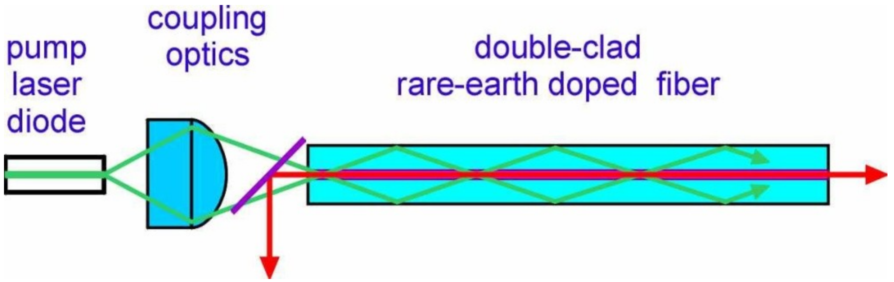


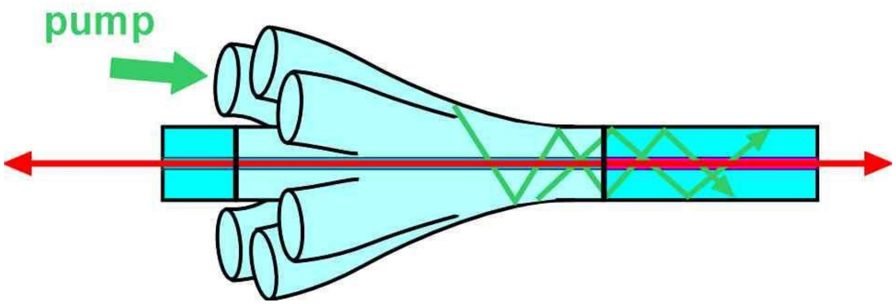


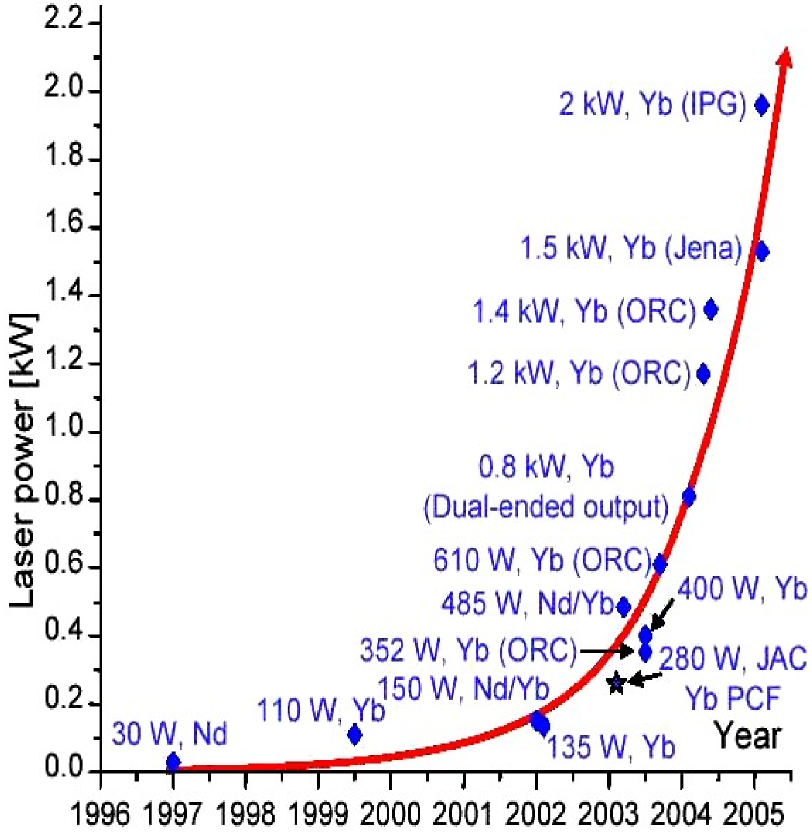
Optical excitation systems



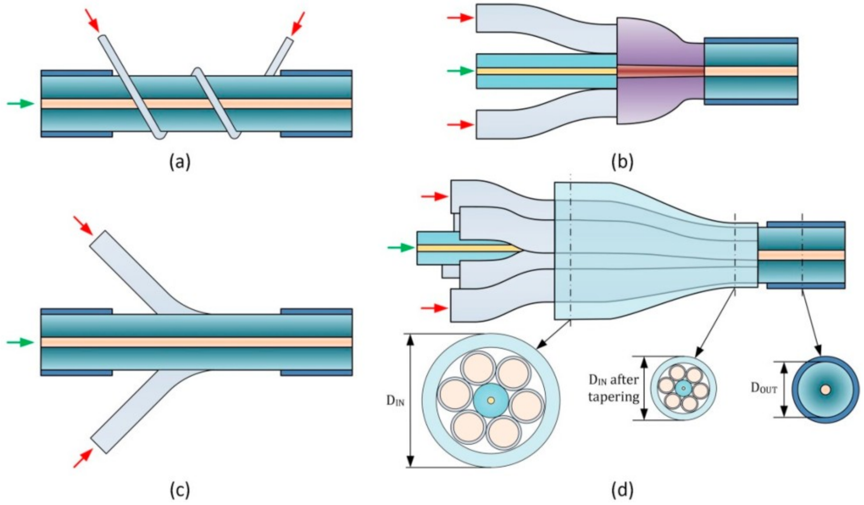


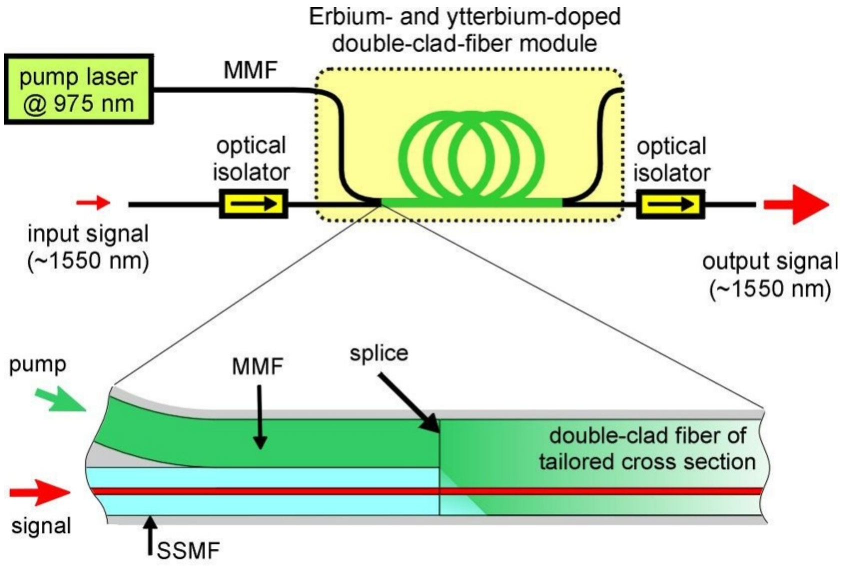


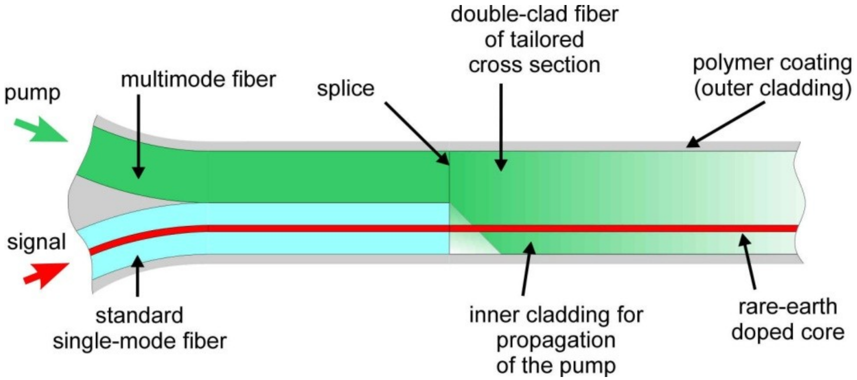




Fiber laser amplifiers

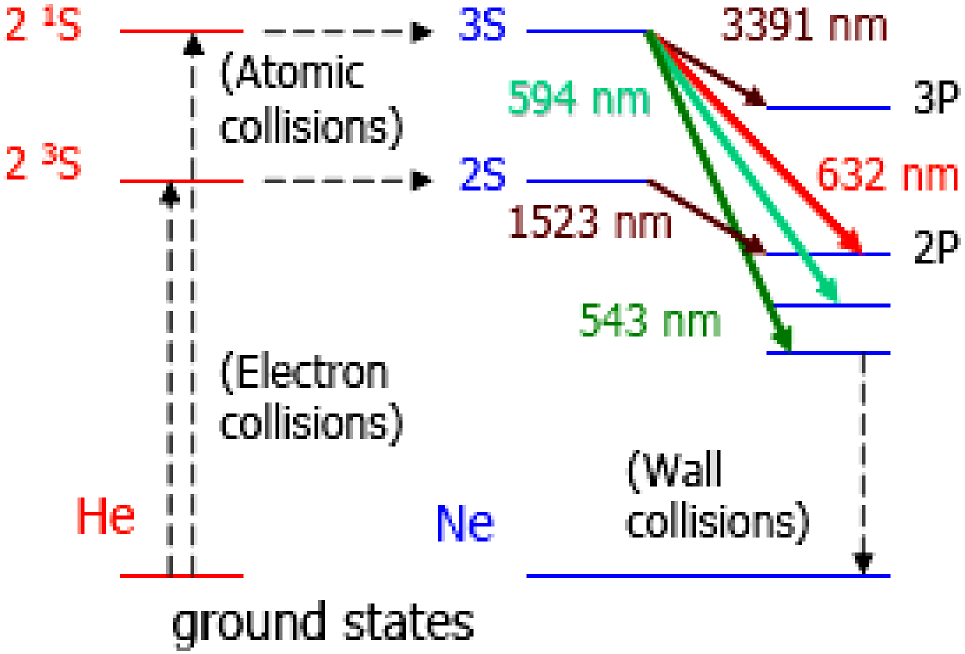






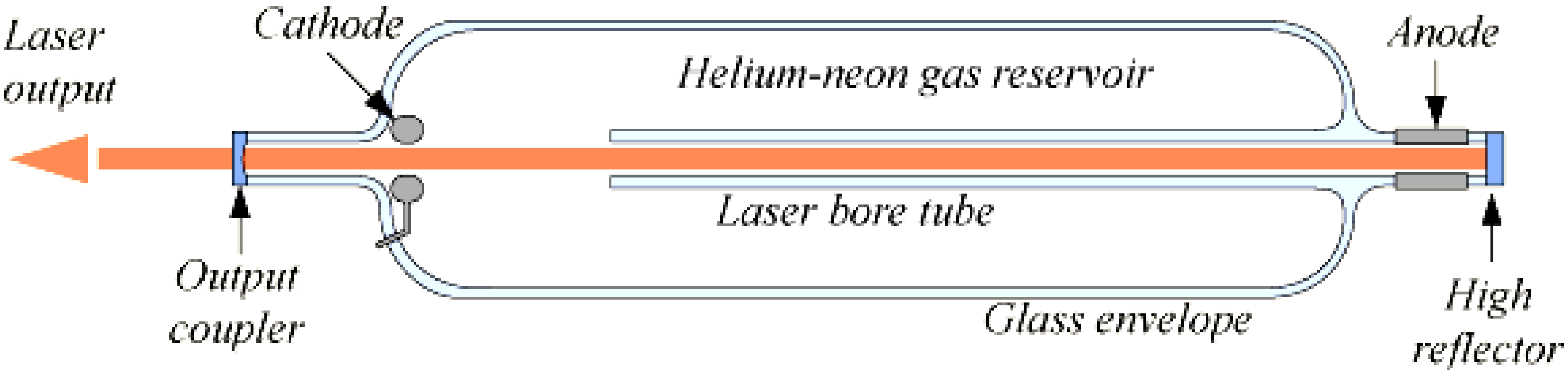
Gas laser He-Ne

- Invented in 1960 as IR laser; red line used first in 1962
- Electric discharge in gas excites He to 2S levels
- Nearly parallel Ne levels exist
- Atomic collisions transfer excitation

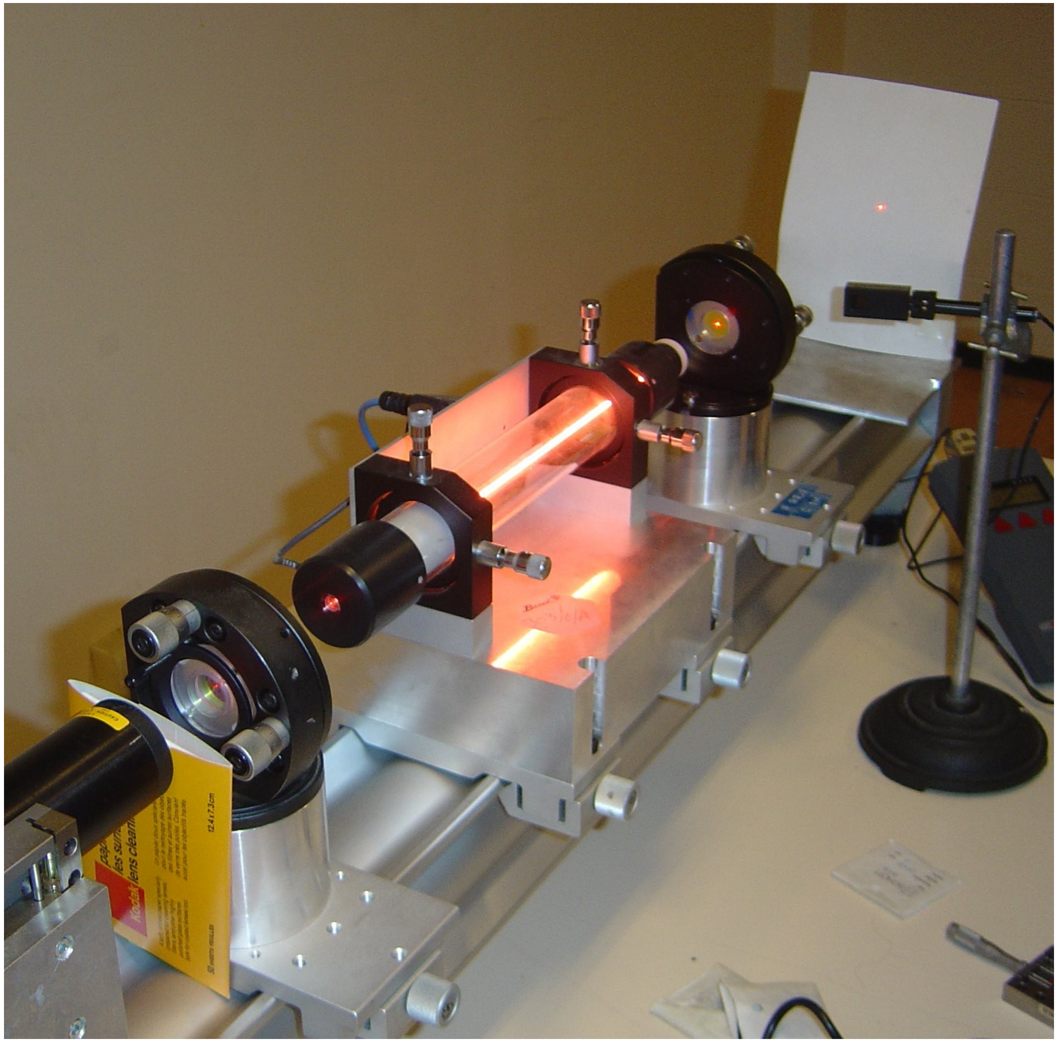


Gas laser He-Ne

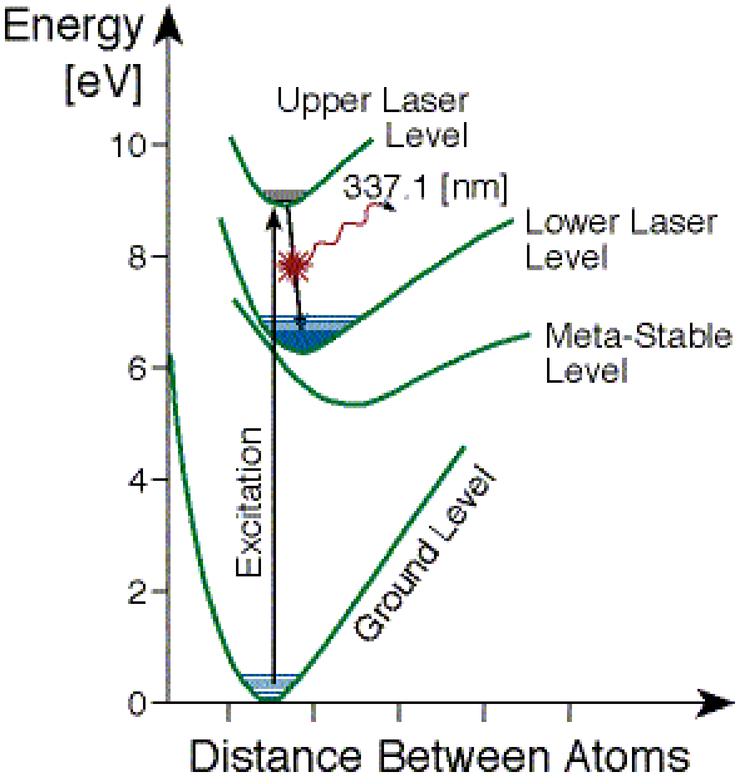
- Cheap and easy to manufacture – first lasers under $100
- Gas tube has 85% He, 15% Ne

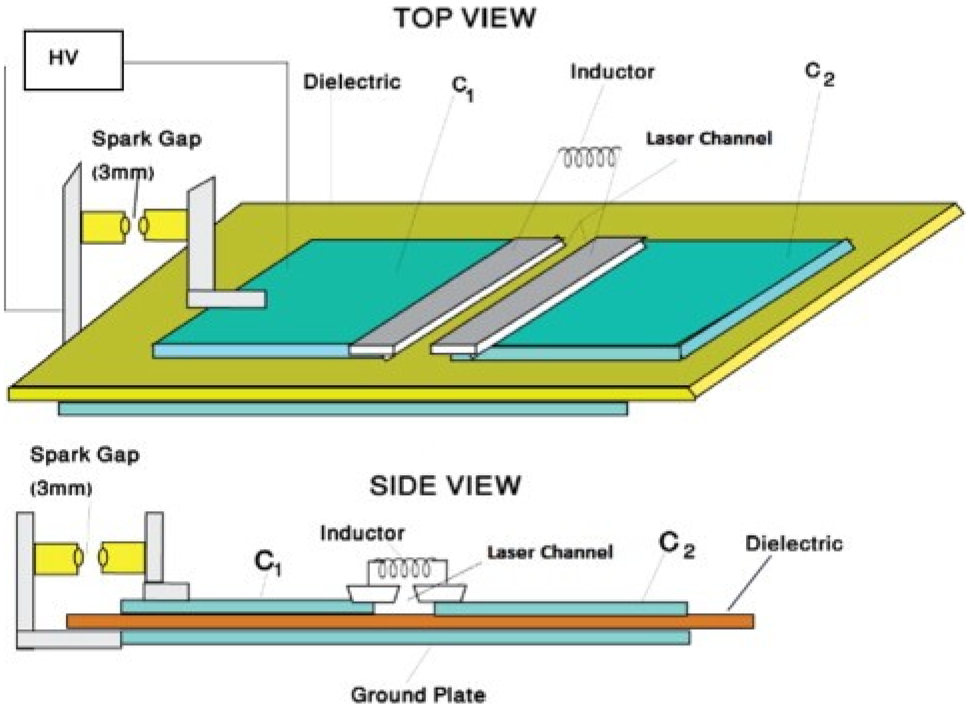


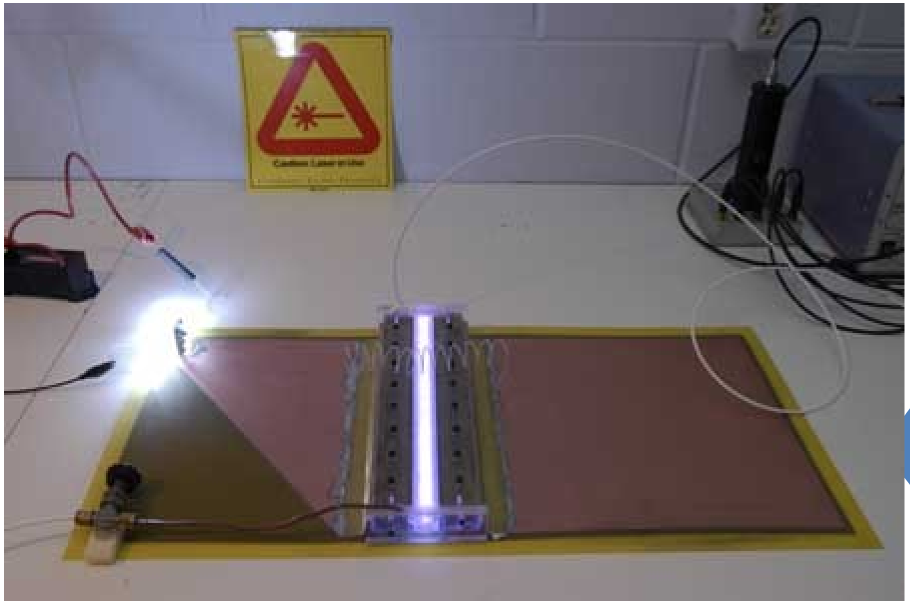
He-Ne laser



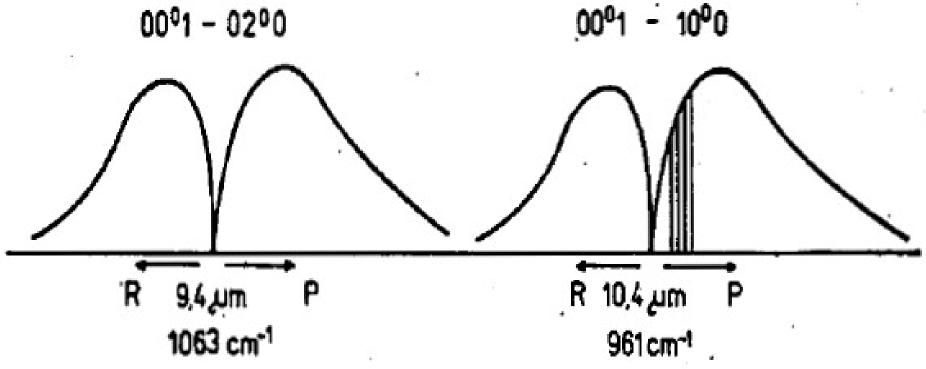
Nitrogen laser



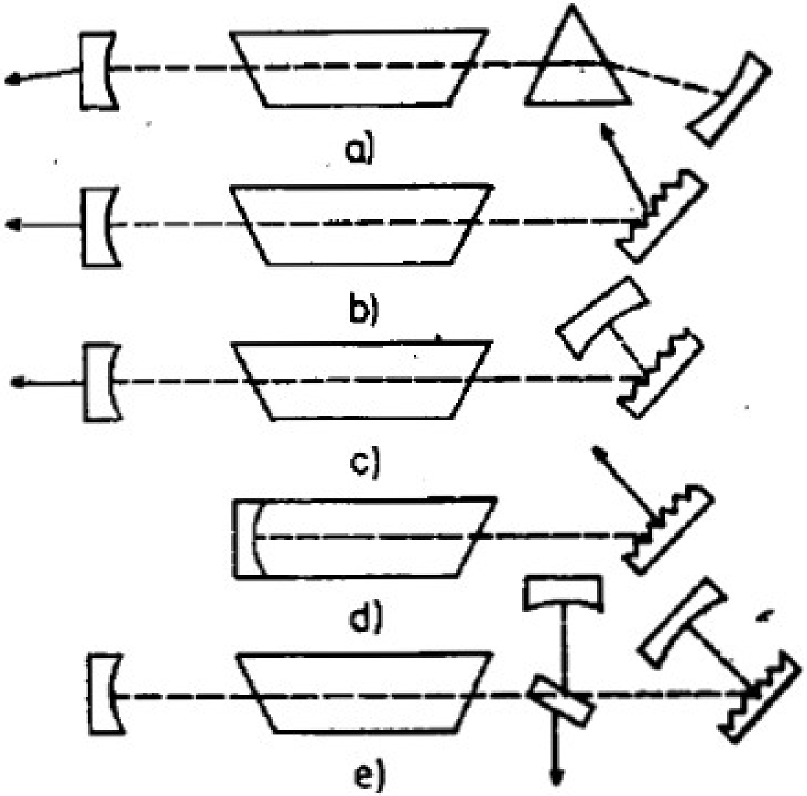




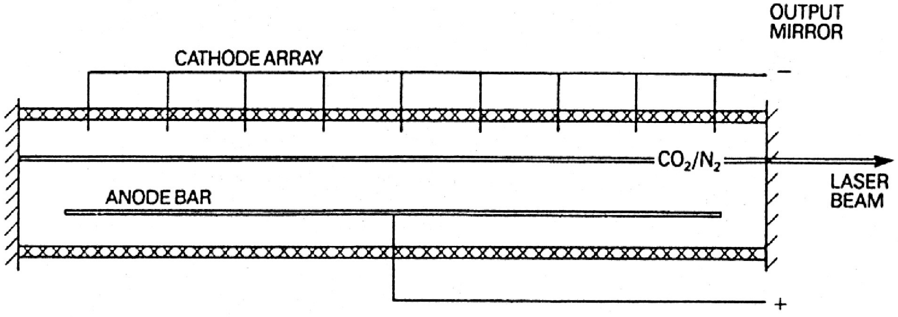
CO2 laser



Waveform intensity of CO2 laser lines

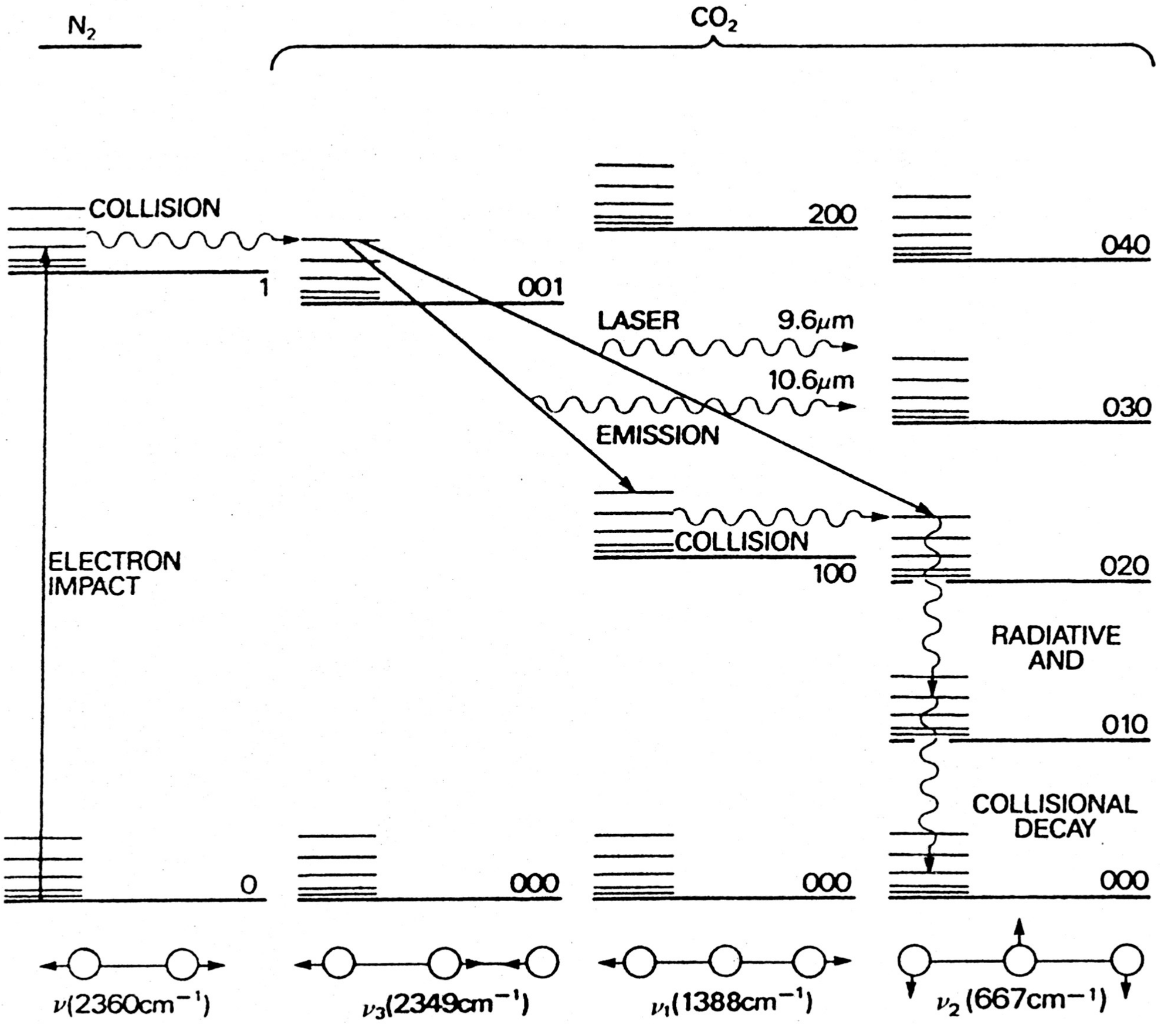


Selection of wavelengths and beam binding



Electrode arrangement in a transverse excitation atmospheric (TEA) carbon dioxide laser

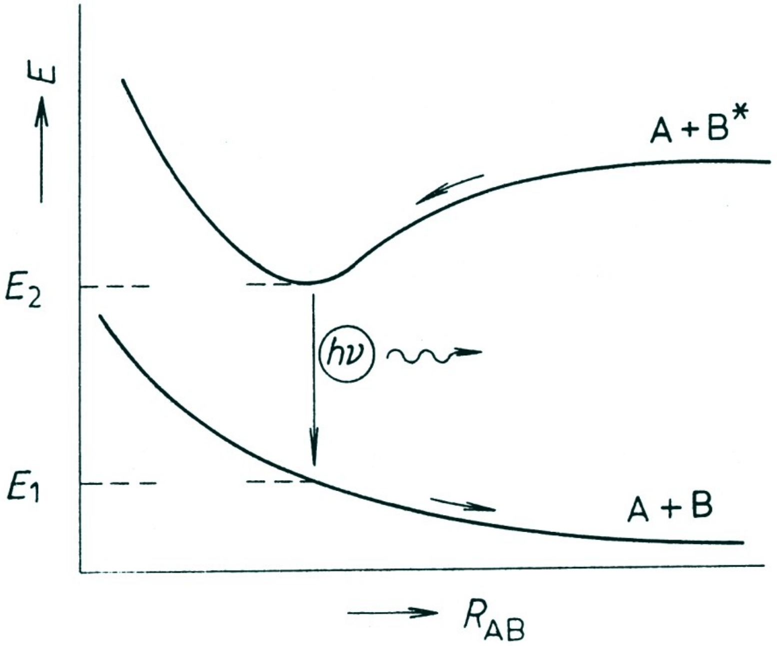
Energetics diagram of CO2 laser



Energetics of the carbon dioxide laser. The rotational structure of the vibrational levels is shown only schematically

Excimer

- Excimer - an unstable molecule formed for a limited time due to the action of an excited atom (molecule) with an atom (molecule) in its base ground state.
- Dissociation occurs within 10-14s after excimer transition to base ground state (photon emission).



Dependence of the potential energy E of an excimer-forming system of atoms (molecules) A, B on their RAB distance

KrF exciplex laser

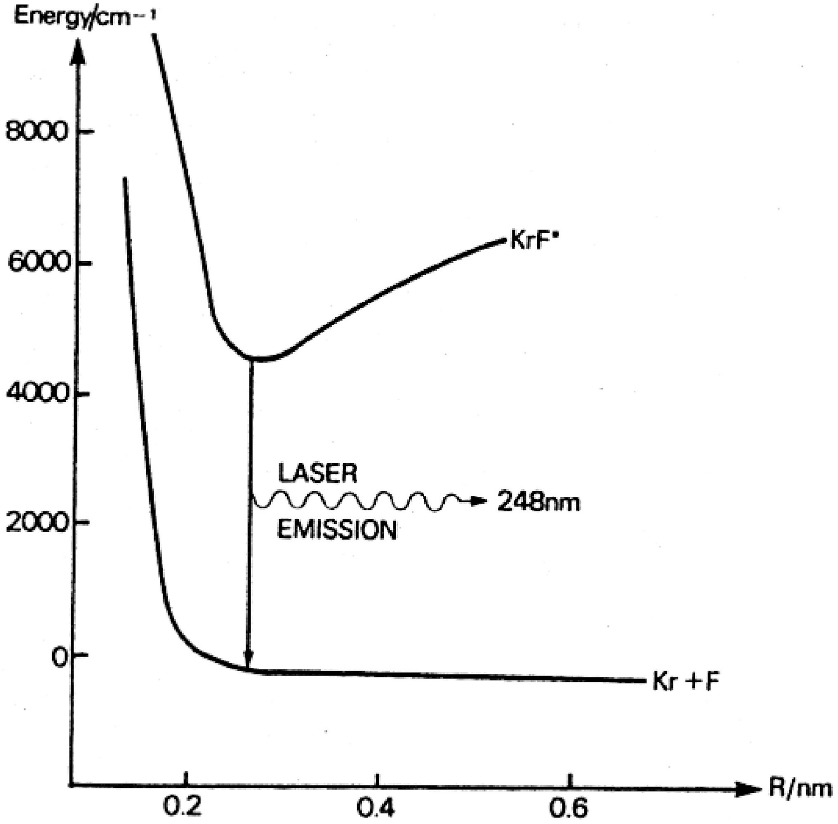
$$Kr + e \rightarrow Kr^+ + 2e$$

$$F_2 + e \rightarrow F^- + F$$

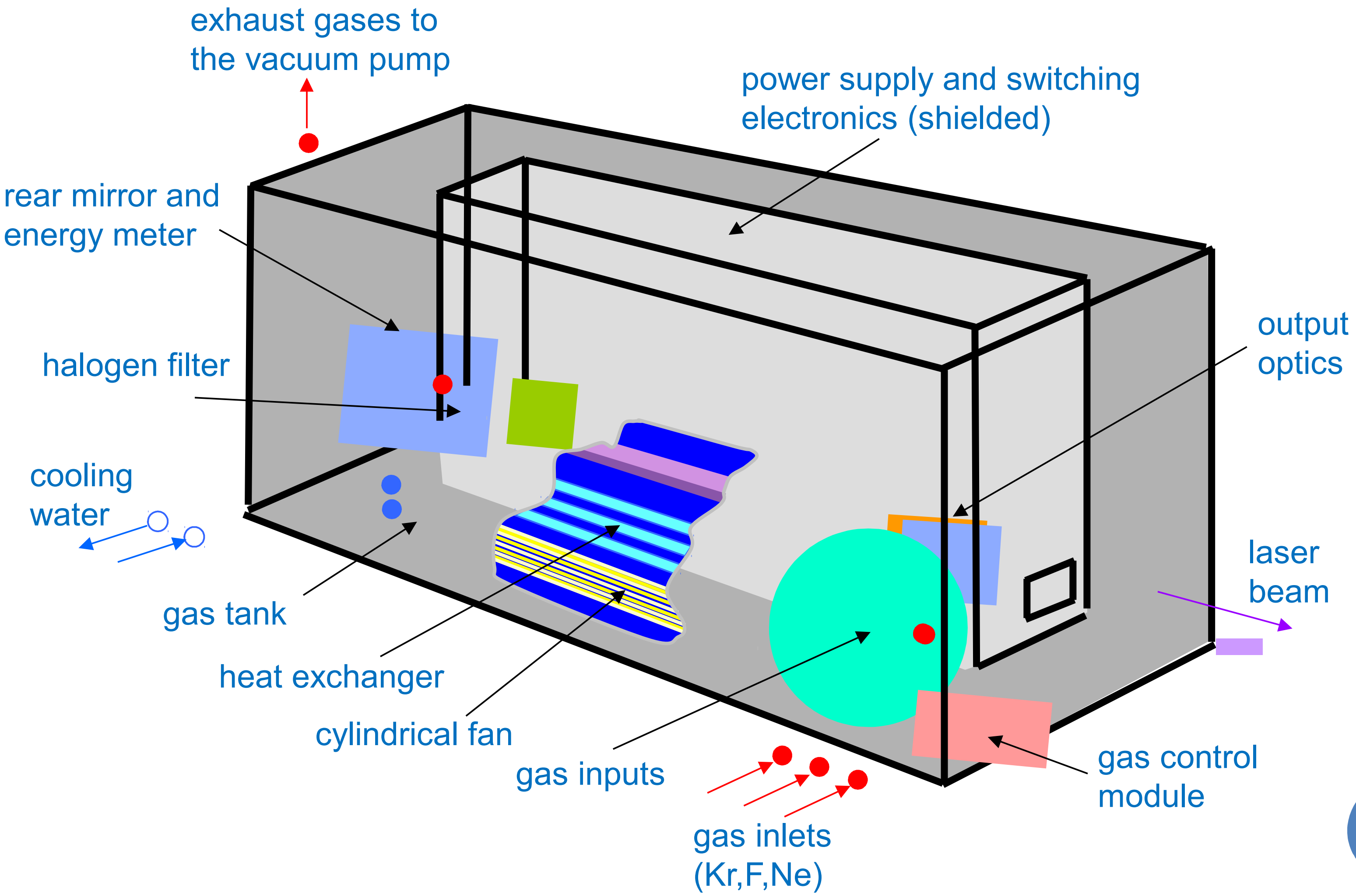
$$F^- + Kr^+ + He \rightarrow KrF^* + He$$

Exciplex - excited complex
Excimer - excited dimer

Realization : 1970 Basov, Xe2*
excited electrons



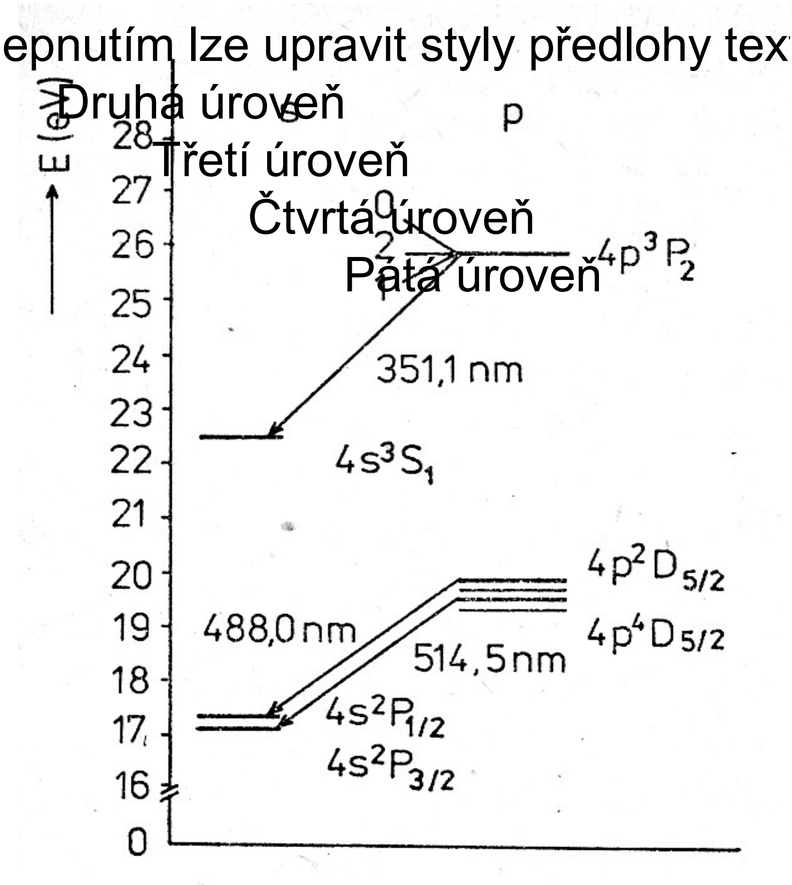
Excimer laser



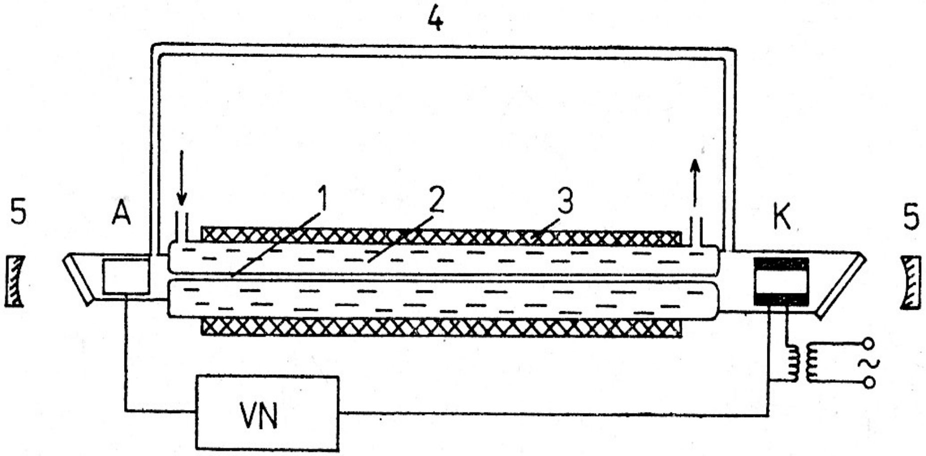
Argon ion laser

Klepnutím lze upravit styly předlohy tex

- Druhá úroveň
  - Třetí úroveň
    - Čtvrtá úroveň
      - Pátá úroveň

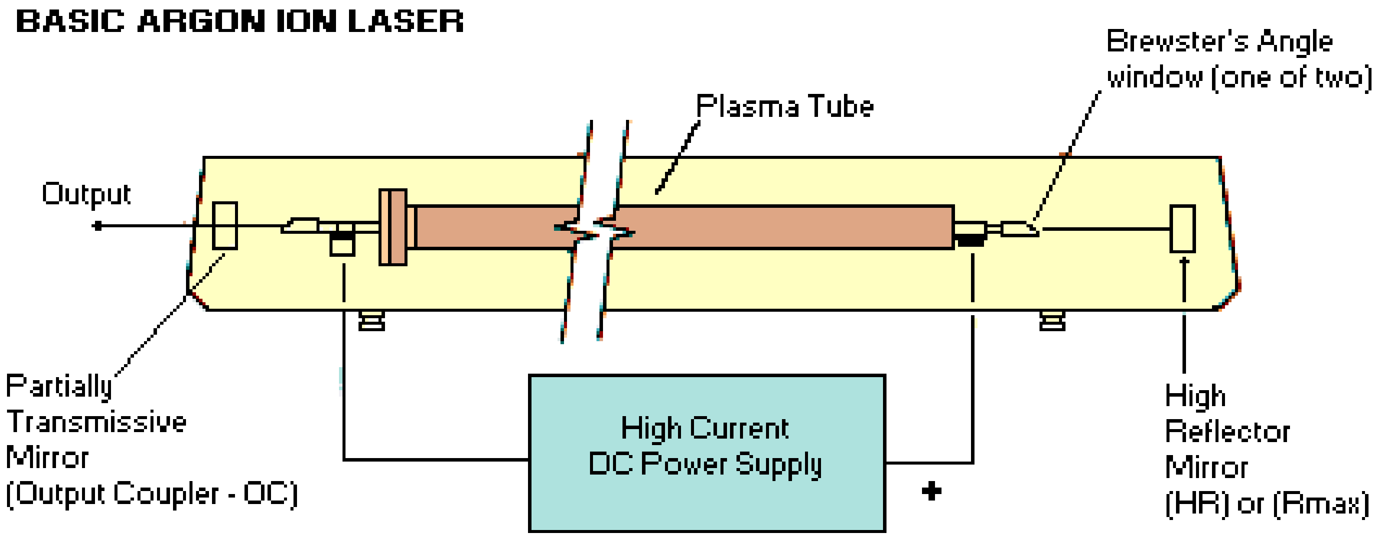


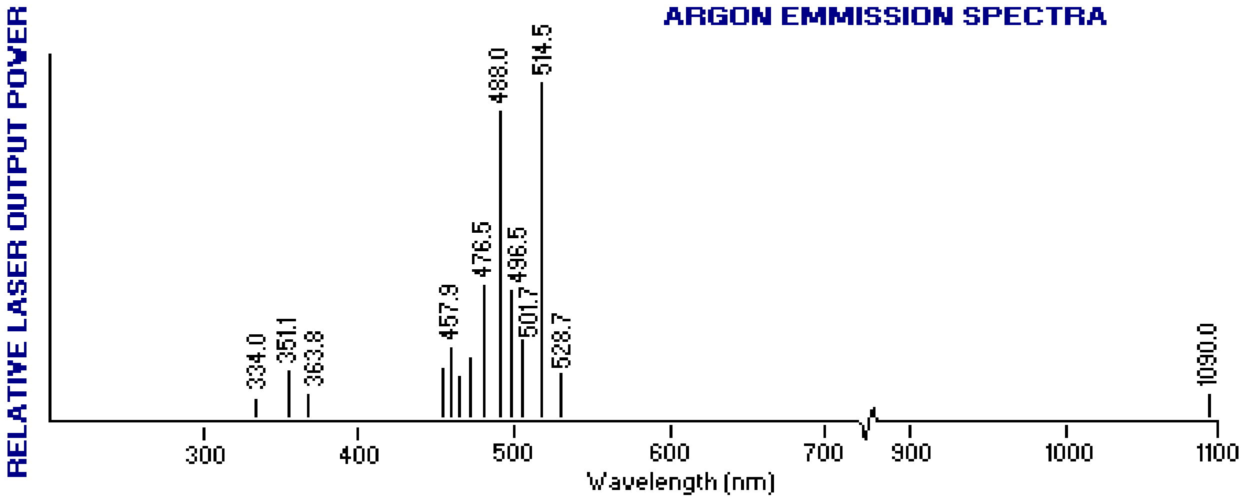
Scheme of transitions ArII and ArIII ions



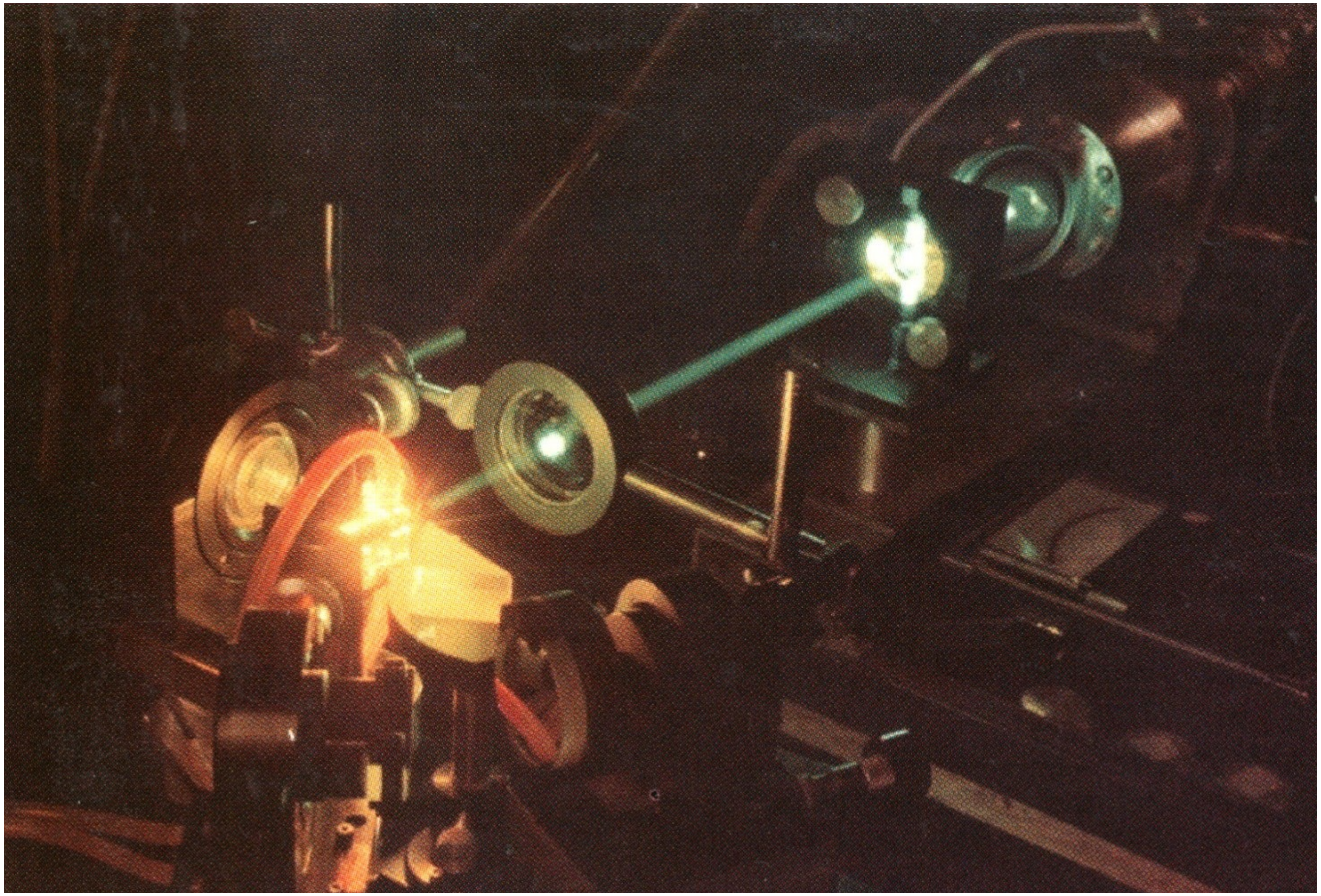
Argon laser scheme:
1-high current capillary
2-water cooling
3-solenoid
4-level capillary
5-mirrors
A-anode, K-hot cathode,
VN - high voltage

Argon ion laser





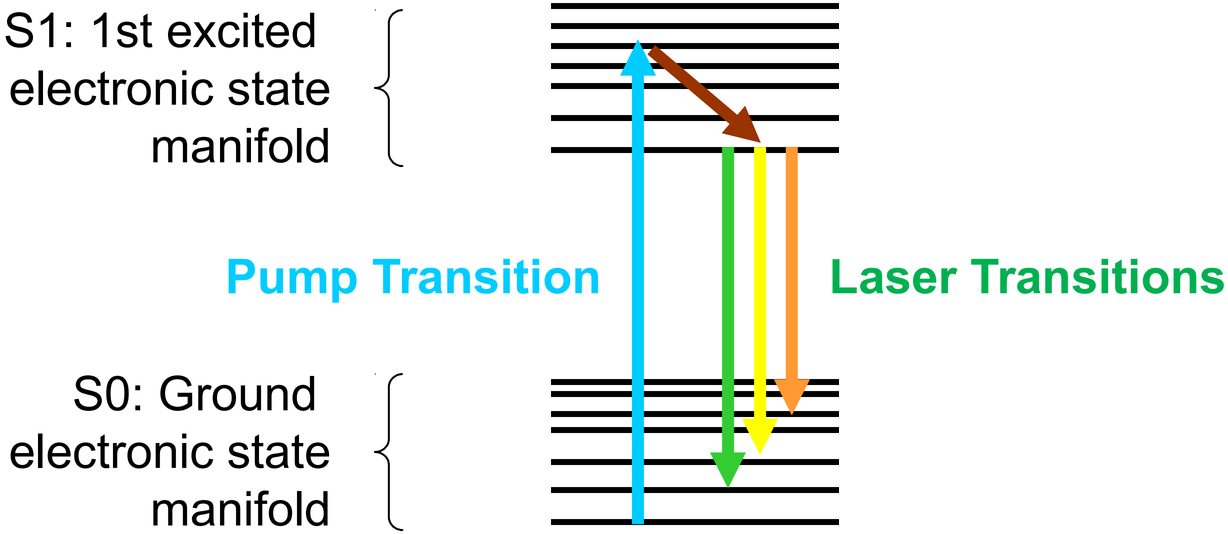
Dye lasers



Dye lasers are an ideal four-level system, and a given dye will laser over a range of ~100 nm.

A dye's energy levels

- The lower laser level can be almost any level in the S0 manifold.



S1: 1st excited electronic state manifold

Pump Transition

Laser Transitions

S0: Ground electronic state manifold

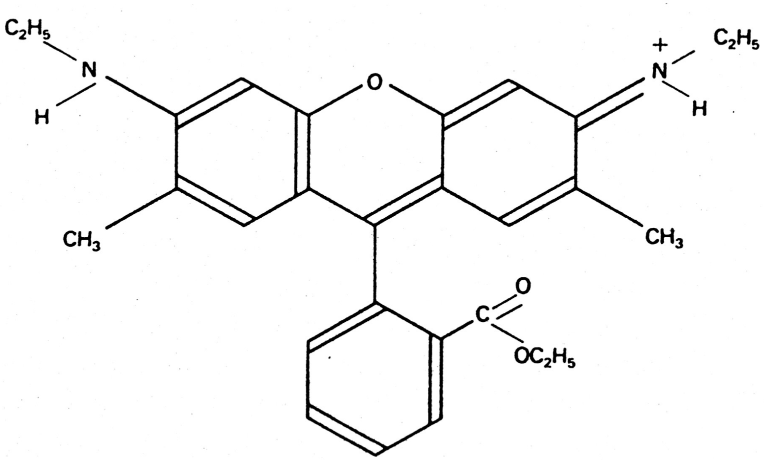
Dyes are so ideal that it's often difficult to stop them from lasing in all directions!

Dye lasers

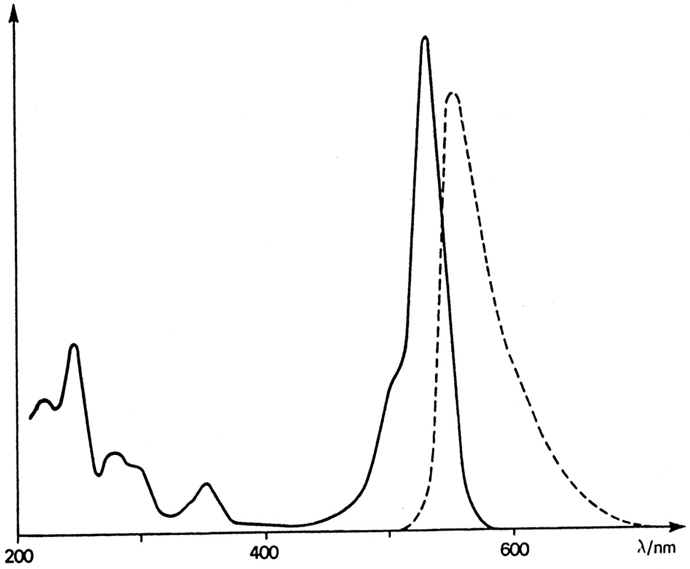
- They are characterized by high spectral bandwidth gain (10 -100 nm) and it follows:

1. Possibility of continuous change of the wavelength of the laser radiation in the range of sufficient gain bandwidth

2. Possibility to generate short pulses, up to 1 ps

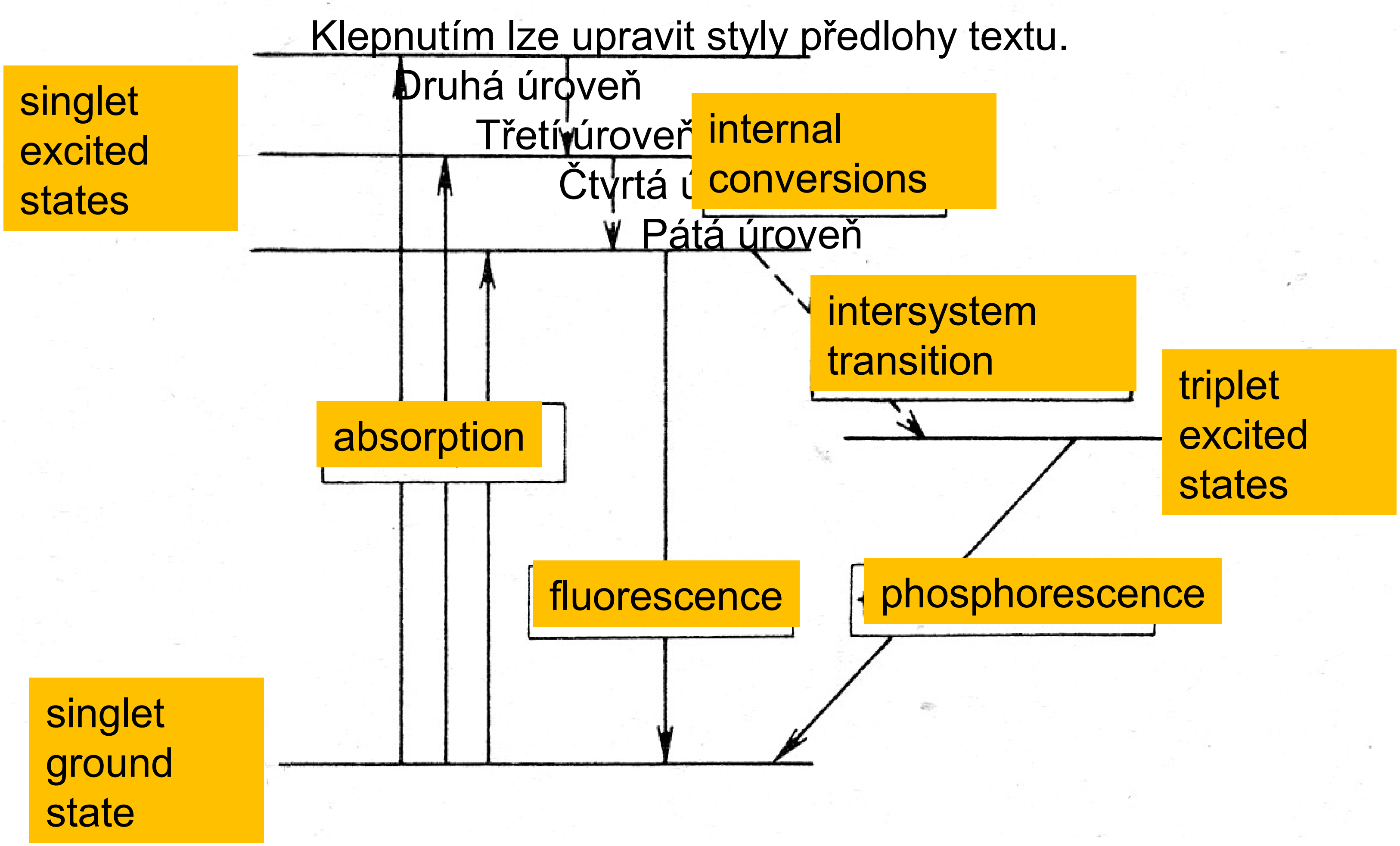


One of the resonance structures of the Rhodamine 6G cation



Solution spectra of Rhodamine 6G in ethanol. The solid curve shows the absorption, and the dotted curve the fluorescence at longer wavelength

Generalized Jablonski diagram of energy levels and dye transitions



- Klepnutím lze upravit styly předlohy textu.
  - Druhá úroveň
    - Třetí úroveň
      - Čtvrtá ú
        - Pátá úroveň

singlet excited states

internal conversions

intersystem transition

triplet excited states

absorption

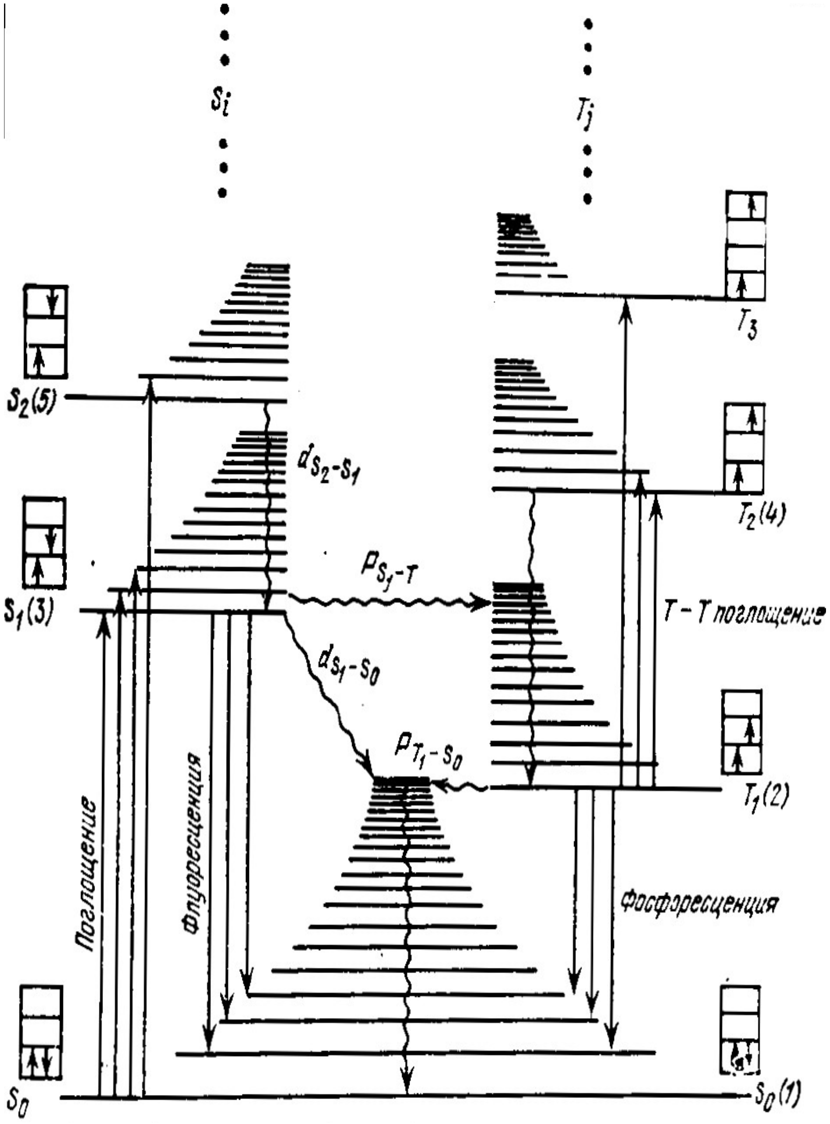
fluorescence

phosphorescence

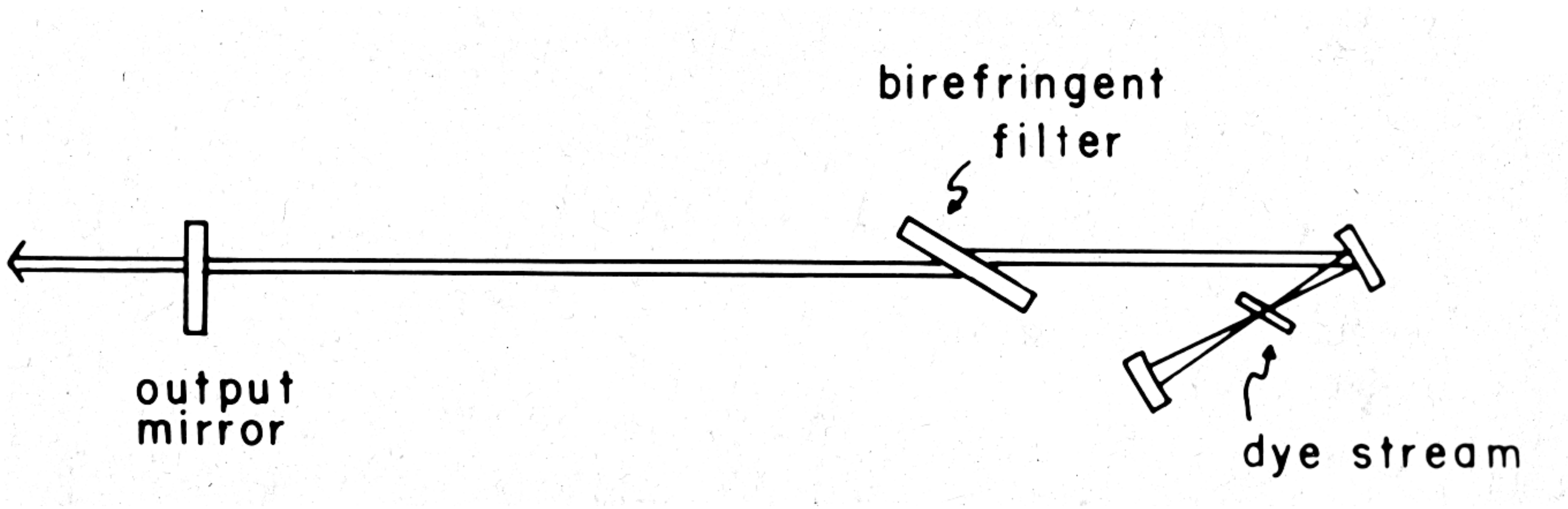
singlet ground state

Dye energy system

- Excitation by absorption of radiation by transition from ground to first singlet state
- Fluorescent transition to the ground state (population inversion possible)
- Non-radiative transition from S1 to metastable triplet T1 state (parasitic process)
- Absorption of fluorescent radiation by T1-T2 (T3) transition - quenches the fluorescence, decreases the gain of the active medium

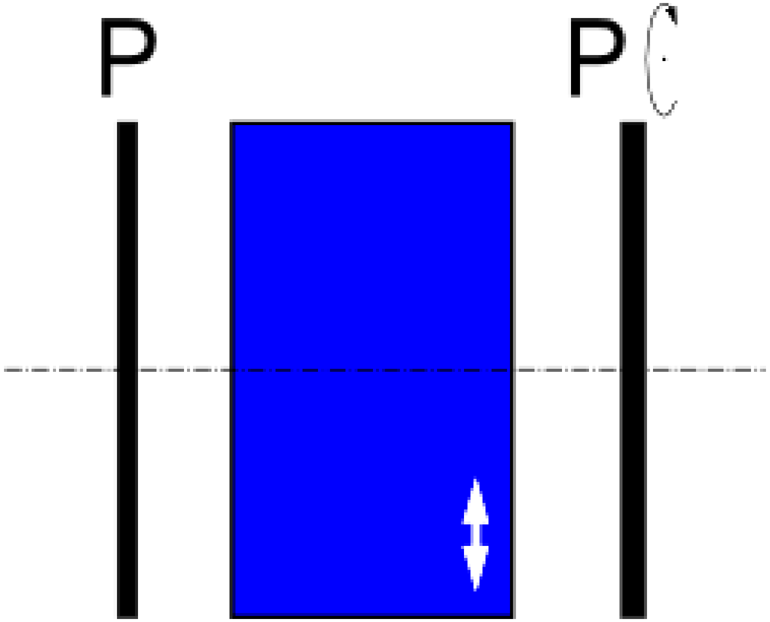


Dye laser - principle



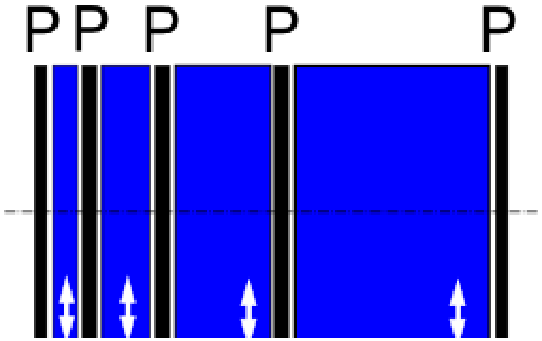
Wood birefringent filters

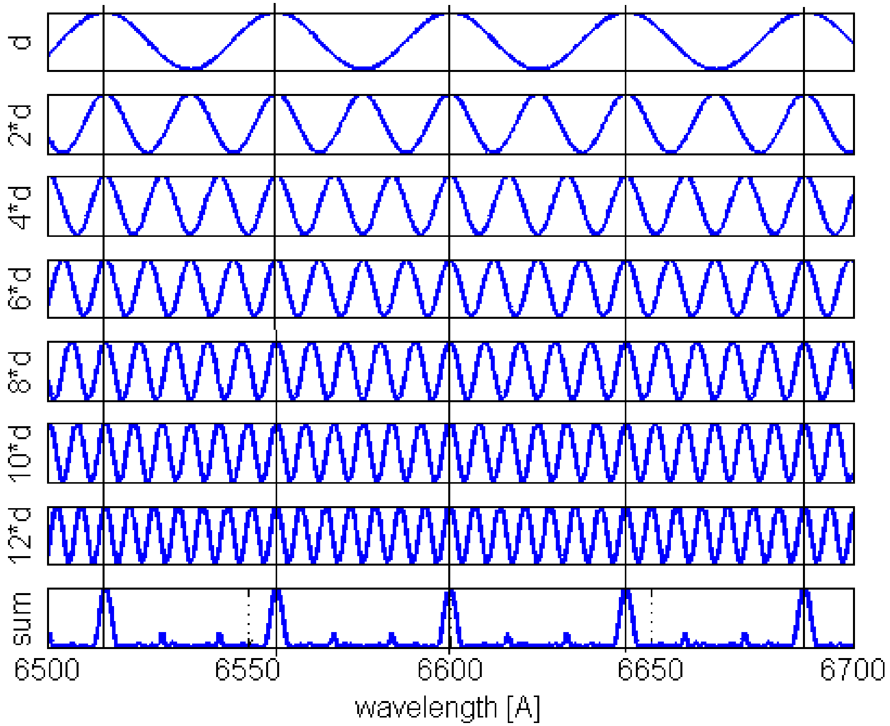
- Wood birefringent filter consists of two polarizers and a crystalline quartz plate cutted parallel with crystal axis. The thickness of the plate depends on wavelengths we want to separate. For already given example of Sodium doublet it gives the thickness of approximatelly 31.8 mm (depends also on operated temperature). These types of filters are very exact optical devices and it is necessary to hold very exact manufacture thickness tolerances.



Lyot birefringent filters

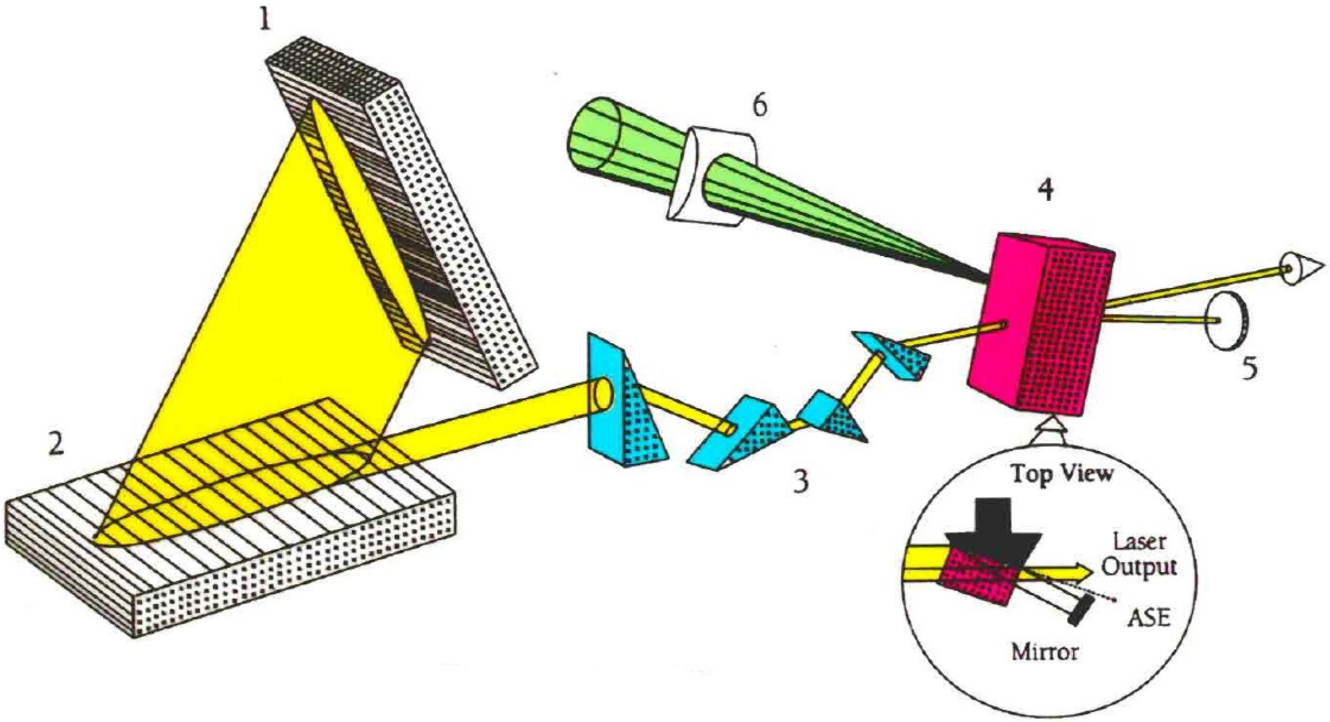
- This filter is in fact constructed from several Wood filters serially lined up. The thickness 'd' of the first plate is such that transmits requested wavelength and provides requested performance of the filter. Each next birefringent plate has a double width of the previous one. That provides two facts; firstly, the requested wavelength is transmitted and secondly, the unwanted transmitted wavelengths of a previous birefringent plate are filtered out. Such a cascade of birefringent plates sandwiched between polarizers provides high performance filter with a half-width in order of 1/1 nanometers



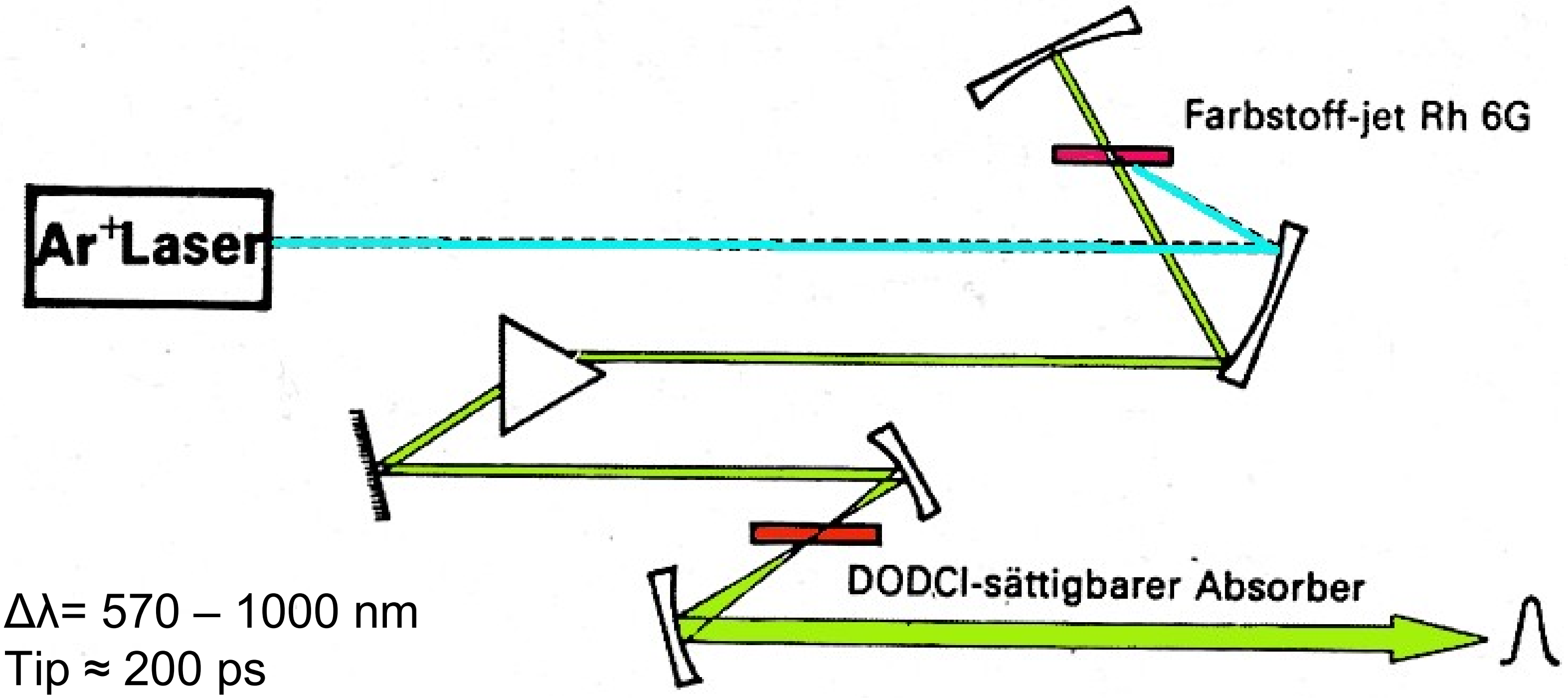


Dye laser

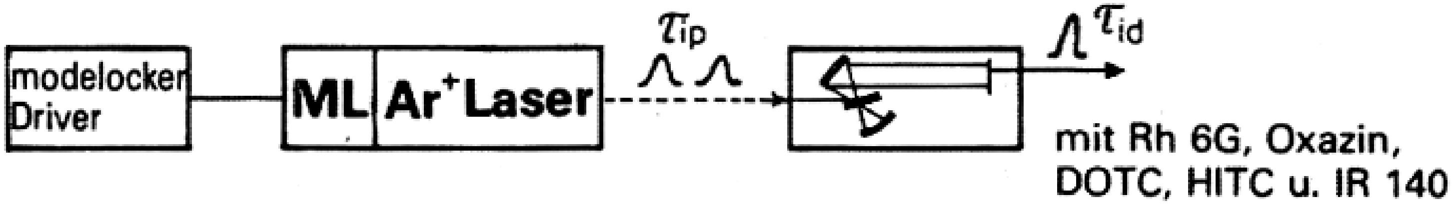
1. Mirror (tuning)
2. Grating
3. Beam expander
4. cuvette with dye
5. Resonator mirror
6. Pumping (by laser)



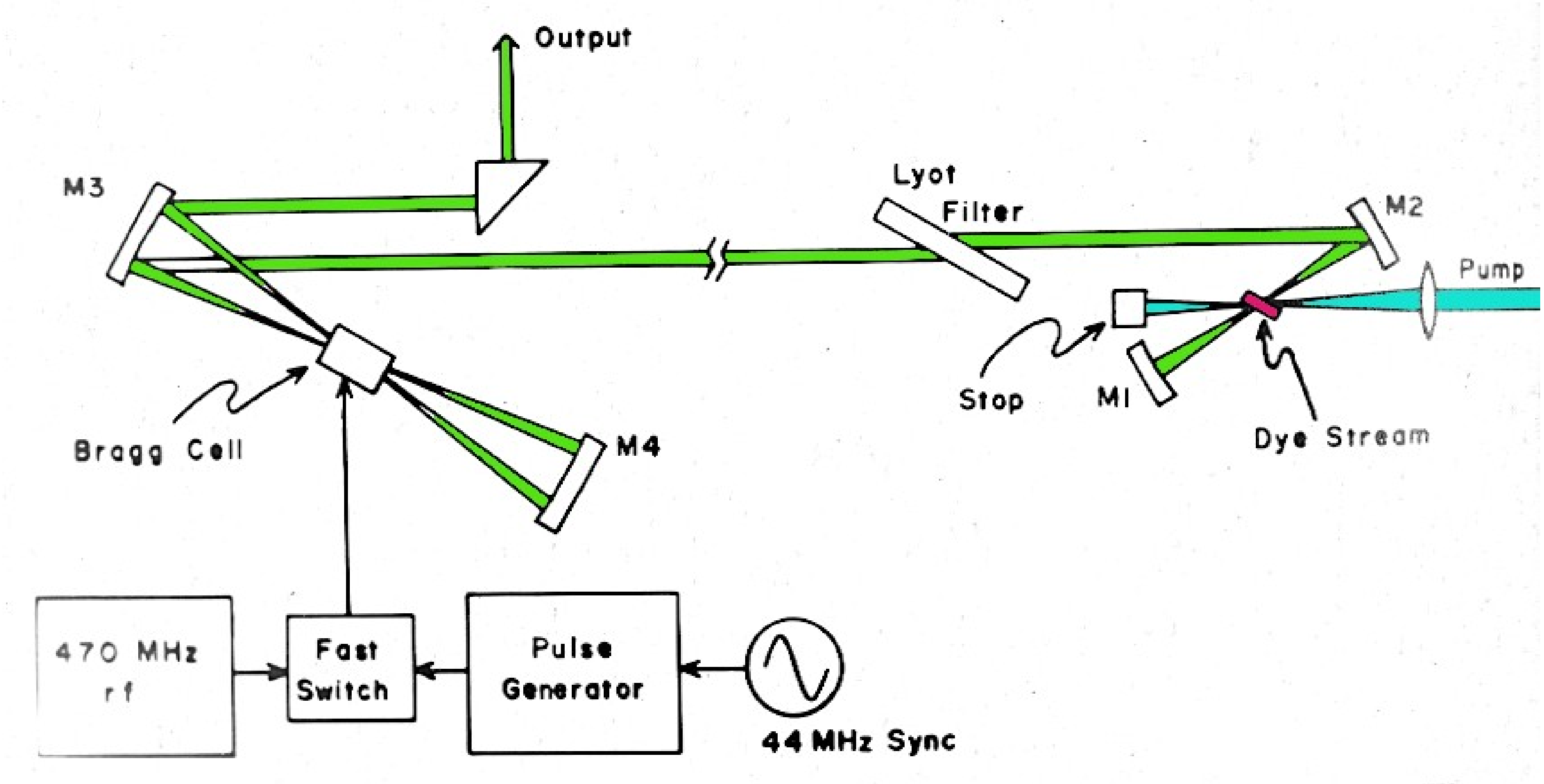
Picosecond laser



Δλ= 570 – 1000 nm
Tip ≈ 200 ps
τid ≈ 0,8 - 50 ps
f = 50 – 150 MHz



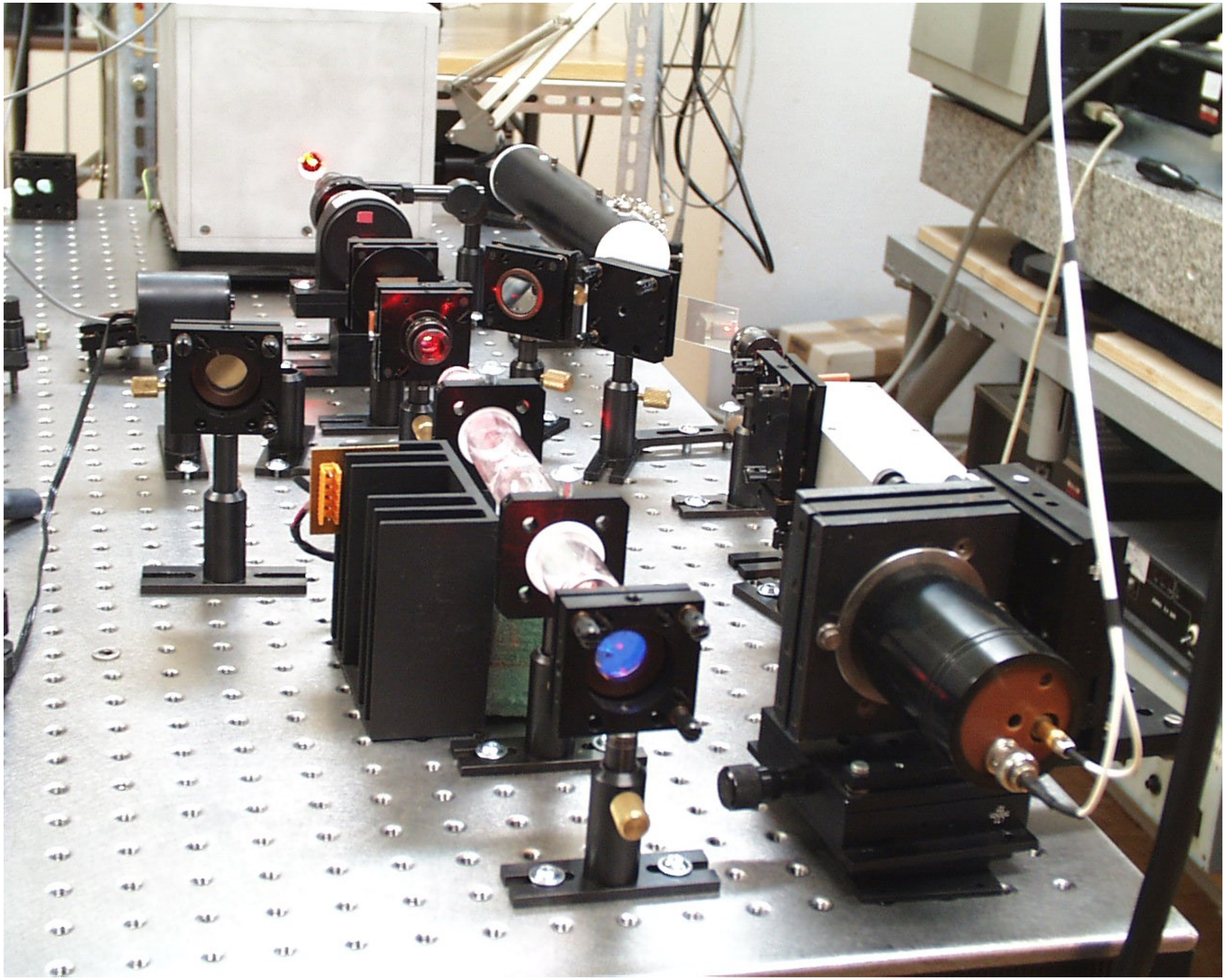
Mode-locked dye laser



Types of dyes for lasers

Emission range (nm)	Structural type
340 - 430	stilbenes
360 - 480	oxazoles
410 - 440	anthracenes
440 - 520	acridines
460 - 540	coumarins
510 - 700	xanthenes
540 - 1200	cyanines
630 – 720	oxazines

Experimental laser workplace

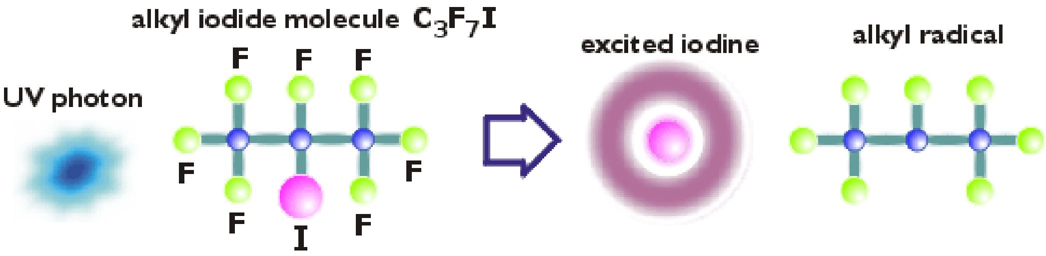


Prague Asterix Laser System

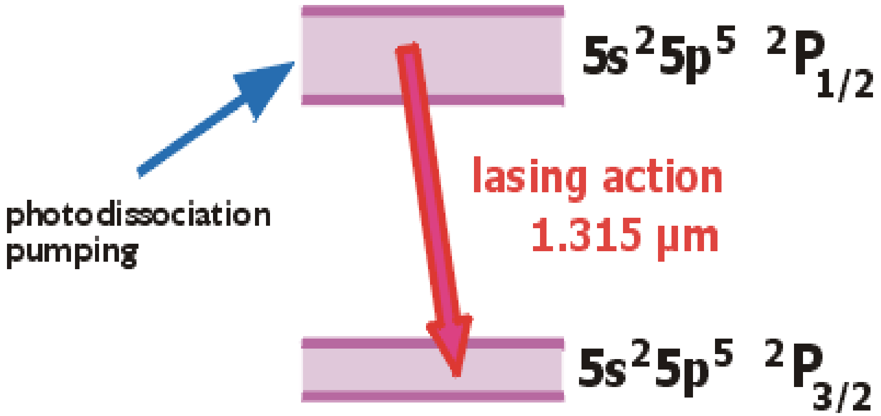
- The backbone of the PALS Research Center is the giant iodine laser system. In its current configuration and at a base wavelength of 1315 nm, it is capable of providing pulses of up to 1 kJ in the main laser beam, in addition to 100 J in two smaller additional beams. The wavelength of the laser beams can be converted to a wavelength corresponding to a second (658 nm, red) or a third (438 nm, blue) harmonic base frequency. Due to the very short laser pulse length (approx. 350 ps), the peak laser pulse power is enormous - up to 3 TW, i.e. 3 million megawatts. The laser is able to deliver such a giant pulse about once every half hour. The PALS output beam is high quality: spatially homogeneous, and stable. Its energy practically does not change from shot to shot.

Asterix iodine laser

Asterix IV is a gas laser in which iodine atoms are used to generate near-infrared radiation at a wavelength of 1,315 µm. The iodine atom is obtained from the parent molecule of the alkyl iodide C3F7I by photodissociation. The atom is released from the chemical bond by means of pulsed UV radiation delivered by the lamps. The electron envelope of iodine emerging from the photodissociation reaction is excited, thereby automatically forming a population inversion with respect to the underlying state. This creates the conditions for the laser action.

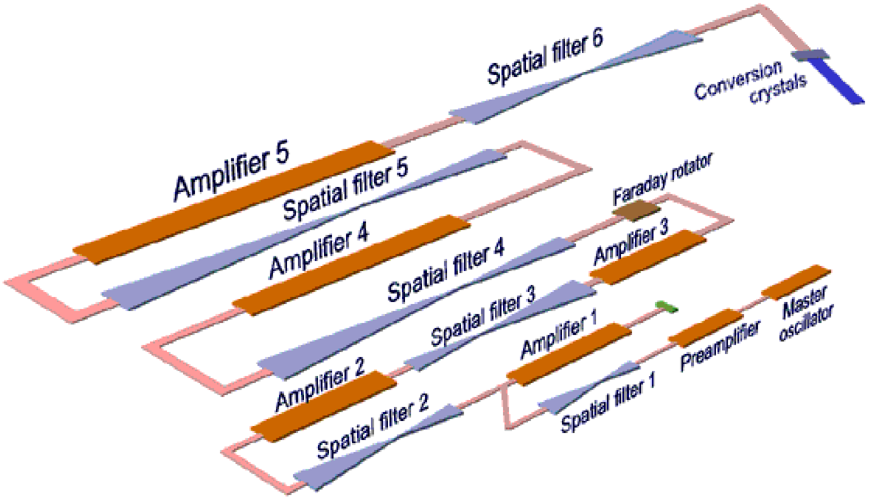


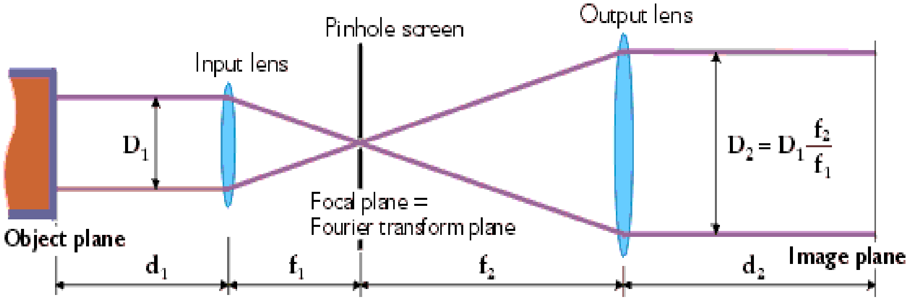
The iodine laser is pumped with energy released via photochemical reaction



The overall arrangement PALS

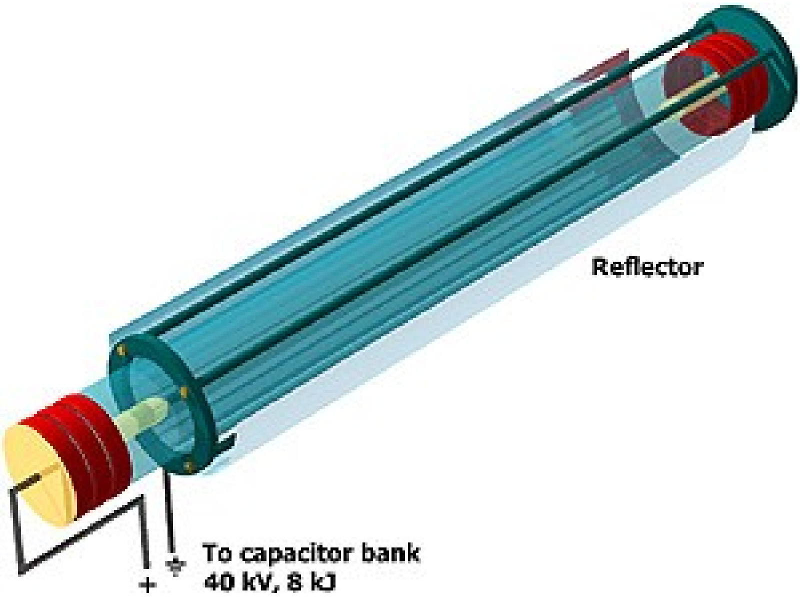
PALS is a single-beam laser system, consisting of an oscillator section generating an initial low light pulse and a string of five laser amplifiers that gradually amplify the pulse. Such an arrangement scheme is called "master oscillator - power amplifiers" (MOPA), or control oscillator - power amplifiers. The size of the amplifiers increases from one amplification stage to the next, so that the diameter of the amplified laser beam gradually increases, from the initial 8 mm to the final 290 mm. In this way, the power density of the laser beam is maintained at a value at which the surface of the individual optical elements cannot yet be damaged by excessive light load.

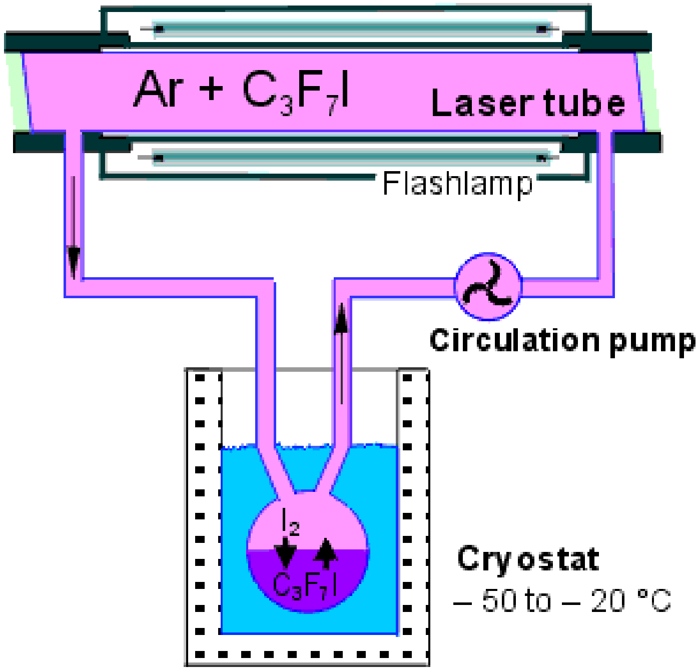




Optical amplifier

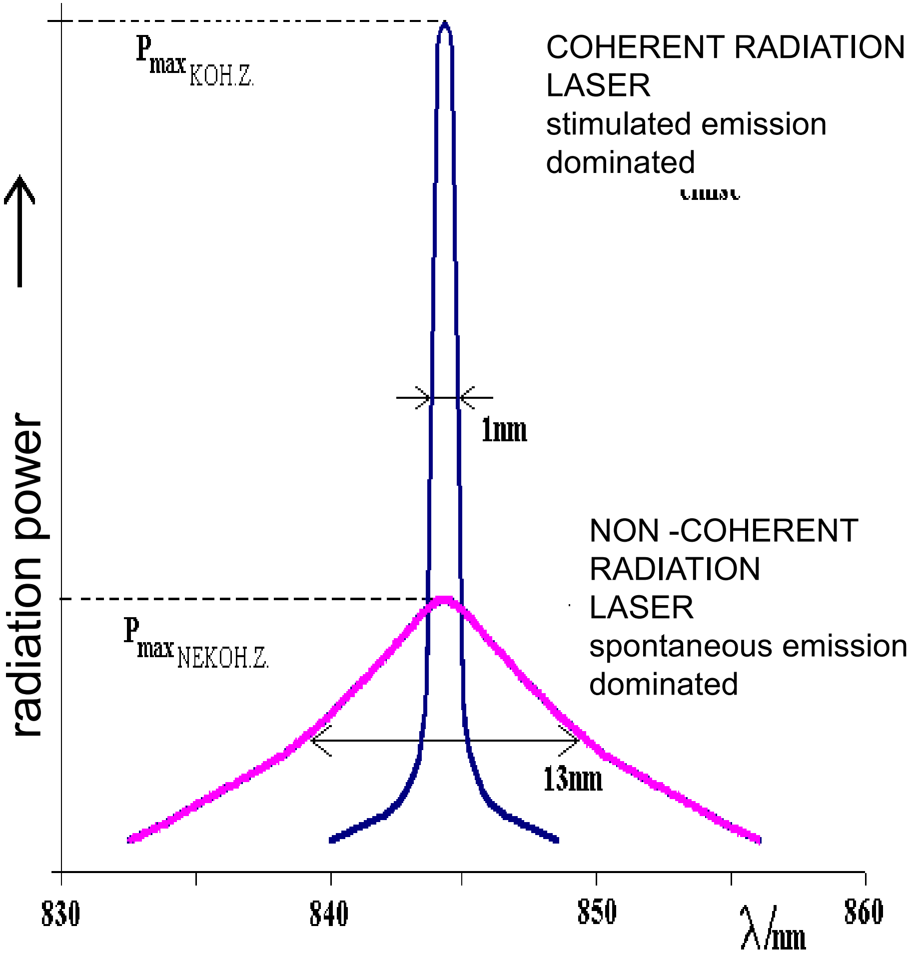
The Asterix IV / PALS laser chain includes a total of five power amplifiers. Their task is to amplify pulses coming from the oscillator to energy up to one kilojoule. The size of each amplifier gradually increases towards the end of the string - the final fifth amplifier is over 13 m long (see picture) and provides a laser beam with a diameter of 29 cm. In the split of second before the actual laser shot, the amplifiers are "activated" by discharging large capacitor batteries into the lamps surrounding the amplifier cells containing the gaseous working environment. The intense pulse of incoherent ultraviolet radiation produced by the lamps gives rise to a large number of excited iodine atoms in the cuvettes, which are "ready" to deliver their excess energy to the laser pulse coming from the oscillator.



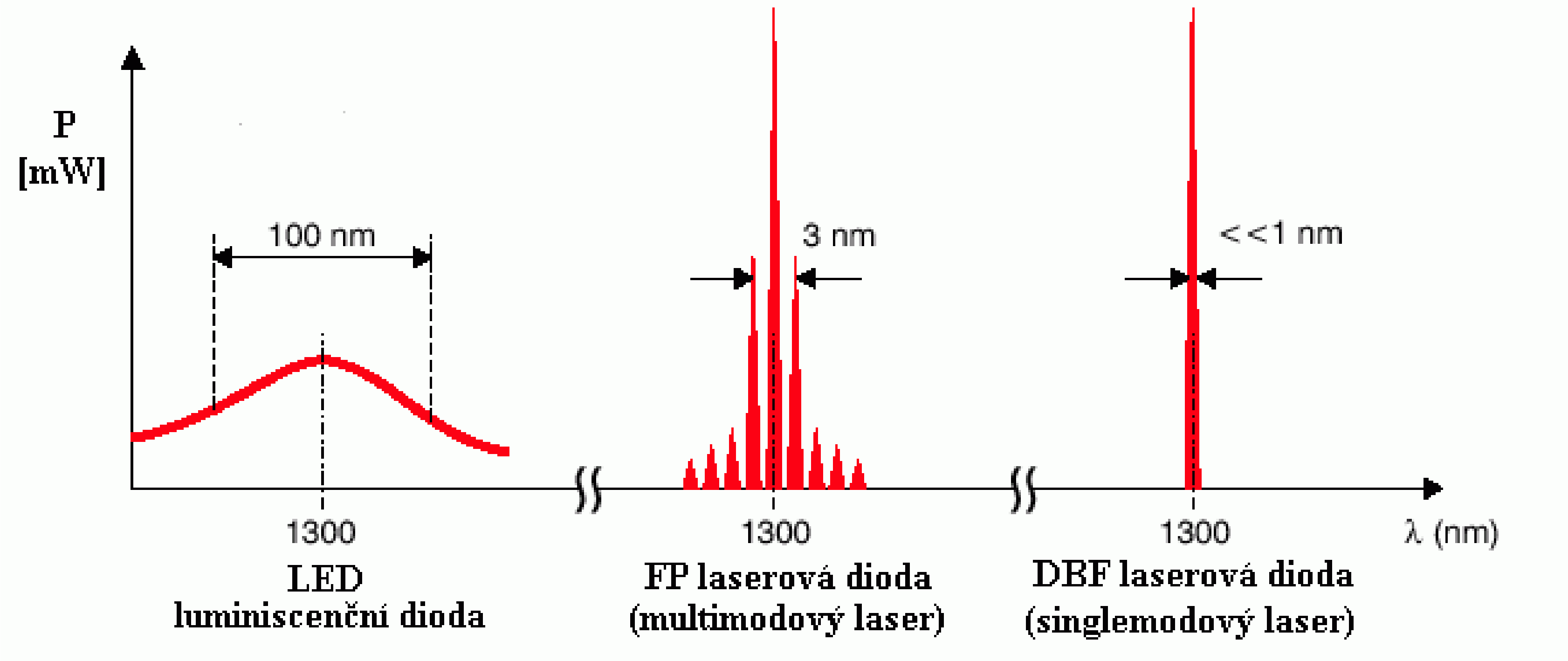


Laser diodes

- For small currents, LED radiation is spontaneous and is a linear function of the excitation current. Upon reaching the threshold current, the power of the stimulated radiation increases sharply and *coherent radiation* is again emitted from the resonator mirrors, again linearly dependent on the magnitude of the excitation current. At the same time, there is a qualitative change in the shape of the radiation characteristic of the laser diode, expressed by decreasing the angle of radiation in a plane perpendicular and parallel to the plane of the PN transition, as well as reducing the bandwidth of the emitted radiation.

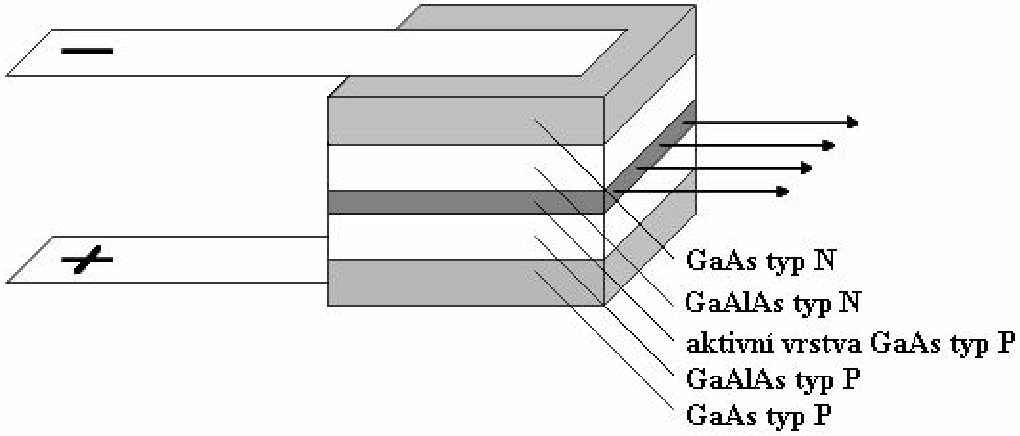


Spectrum of LEDs and laser diodes



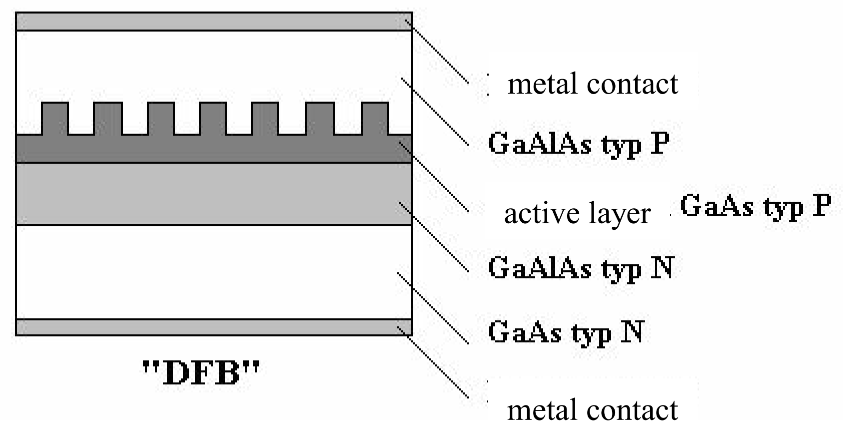
Heterostructure lasers

- In these types of laser with *hetero-transitions*, the delimitation of the waveguide is determined by a sharp change of the refractive index in the region of *hetero-transition*. Along with efficient light guidance, *heterostructure* provides conditions for effective concentration of minority carriers. The effect of hetero-transition concentrates radiation and injection carriers in selected areas.



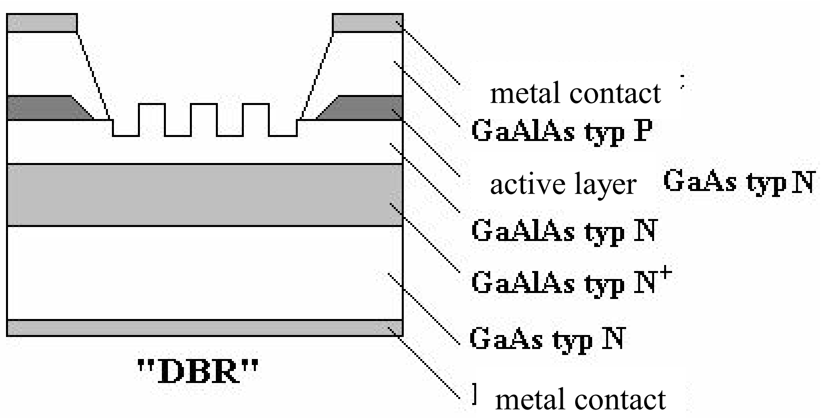
Distributed Feed Back Lasers

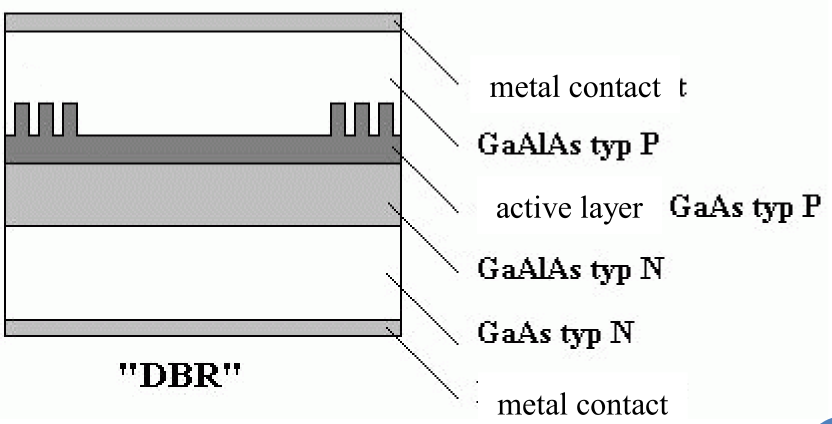
- In this type of laser, the resonator is realized without mirrors using spatial periodic structures (diffraction gratings). The function is based on periodic change of refractive index in the direction of propagation. The feedback is created by the continuous binding of the propagating wave in the opposite direction by Bragg scattering. The grid is formed by etching directly on the surface of the active layer.
- These lasers are referred as DFB



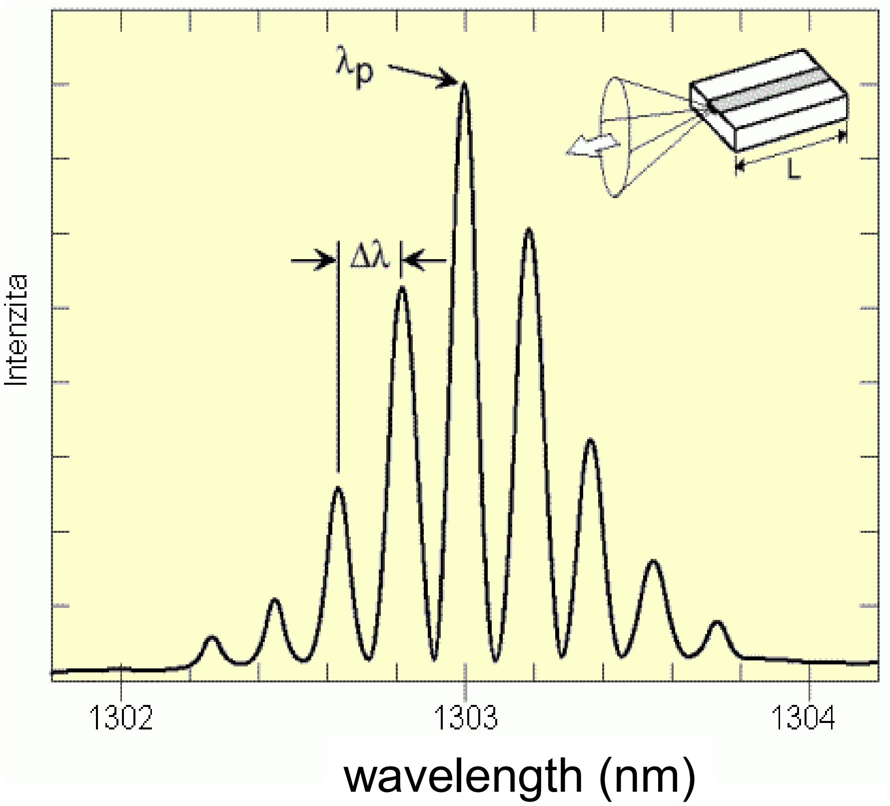
Distributed Bragg Reflector Lasers

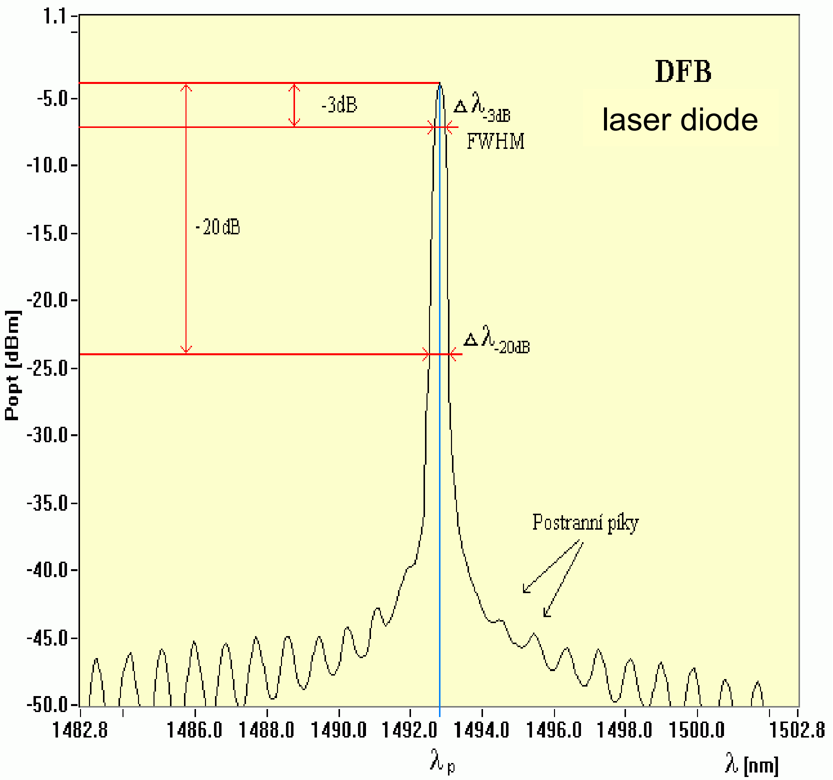
- Optical radiation generation and feedback (again using an optical gratings) take place in separate parts of the structure. Two types of construction are used, with one or two Bragg mirrors. In common practice, the type with two Bragg mirrors at the ends of the waveguide is more often used





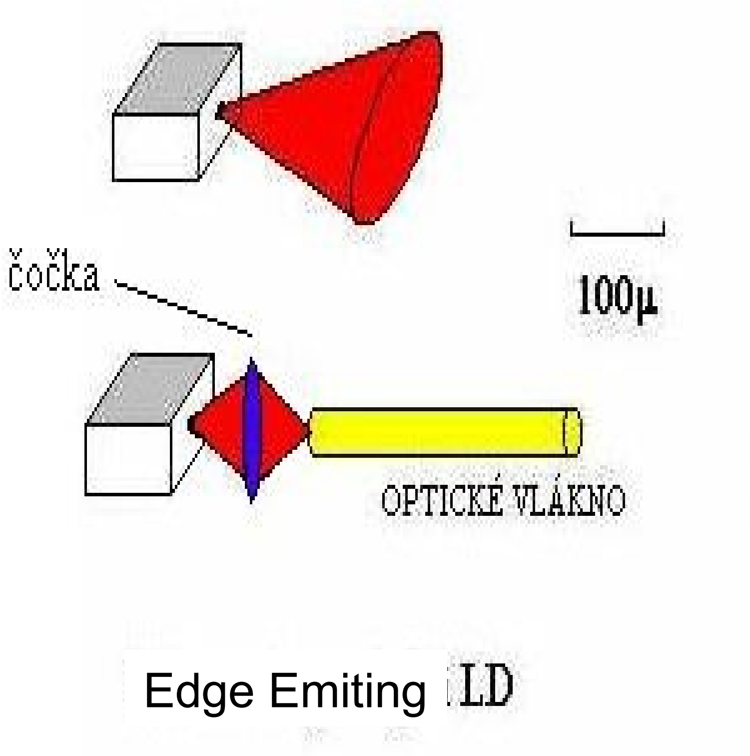
Spectrum of laser diodes





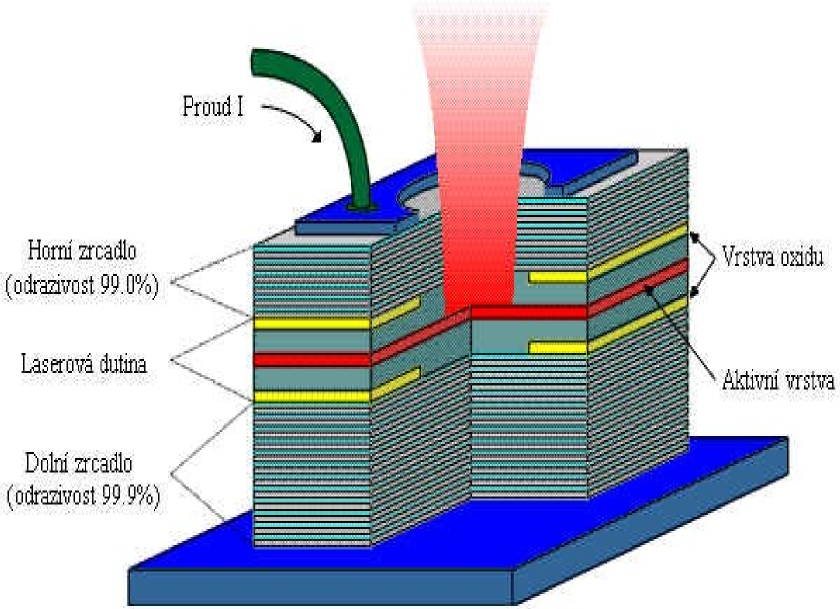
Edge-emitting lasers

- This type (Edge Emiting Lasers - EEL) emits radiation from the edge transition. Manufacturing and applications of laser diodes currently prevails



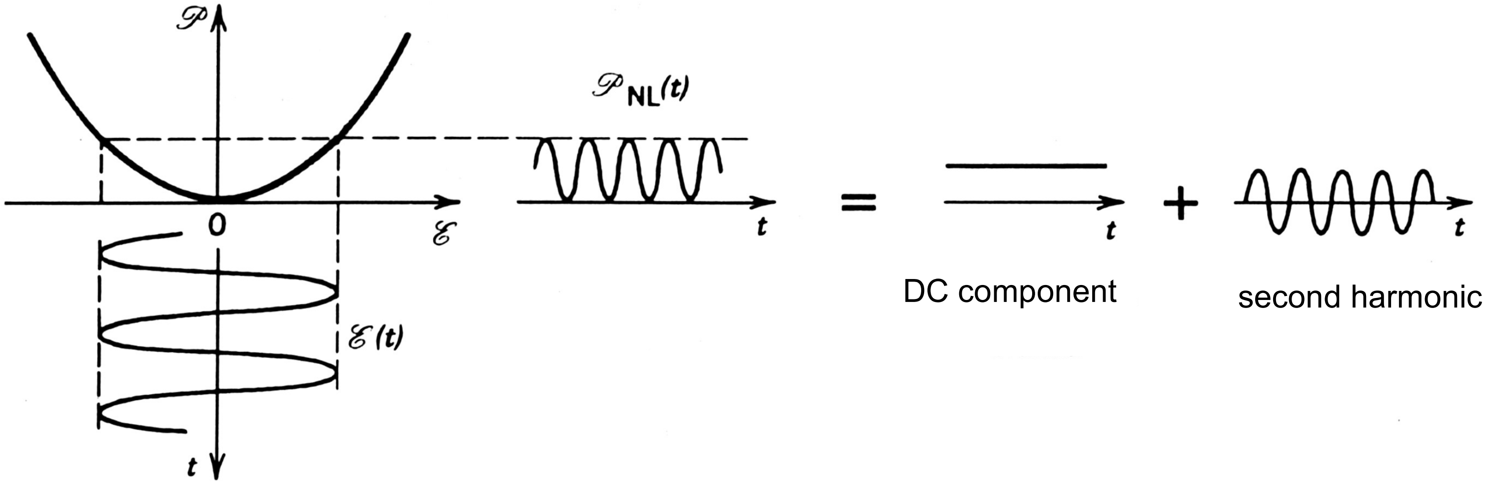
Surface-emitting lasers

- VCSEL (Vertical Cavity Surface Emiting Lasers) emit radiation from the part surface parallel to the transition plane. Radiation emitted from the surface is absorbed by the substrate and lost or, more preferably, is reflected from the metal contact



Frequency conversion

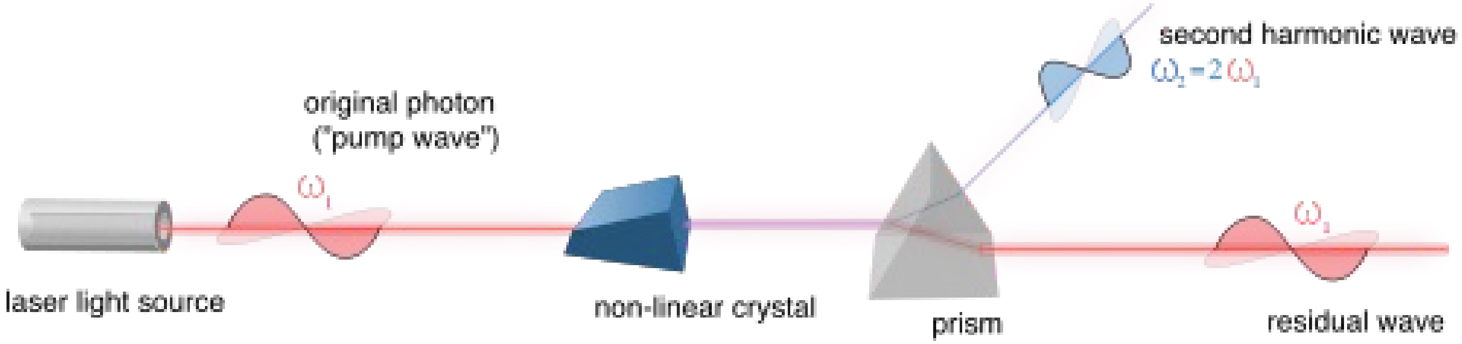
- The first option is to use nonlinear phenomena of the second (third) order. The intensity of the second harmonic radiation is proportional to the square of the coefficient of optical non-linearity and the intensity of the incident wave, inversely proportional to the square of the wavelength.

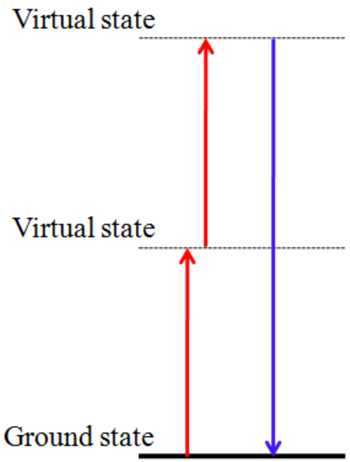


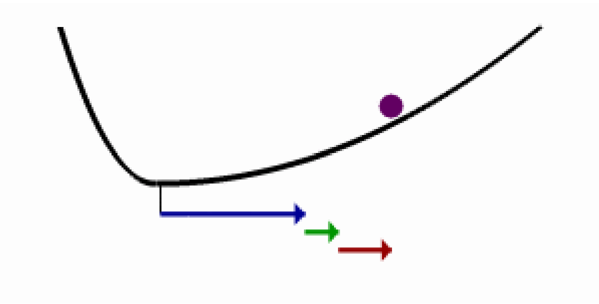
Nonlinear optics - crystals

crystal	Δλ (μm)	MW/cm2
KDP (potassium dihydrogen phosphate)	0,2-1,35	400
KDDP (deuterated KDP)	0,2-1,8	500
ADP (ammonium dihydrogen phosphate)	0,2-1,2	500
RDP (rubidium dihydrogen phosphate)	0,2-1,5	300
CDA (cesium dihydrogenrsenate)	0,26-1,6	500
LiIO3	0,3-4,5	60
LiNbO3	0,4-4,5	120
Ba2NaNb5O15	0,38-5	100
HIO3	0,4-1,3	100
BBO (β-BaB2O4)	0,2-1,5	400

Frequency conversion







The blue arrow corresponds to ordinary (linear) susceptibility, the green arrow corresponds to second-harmonic generation, and the red arrow corresponds to optical rectification.

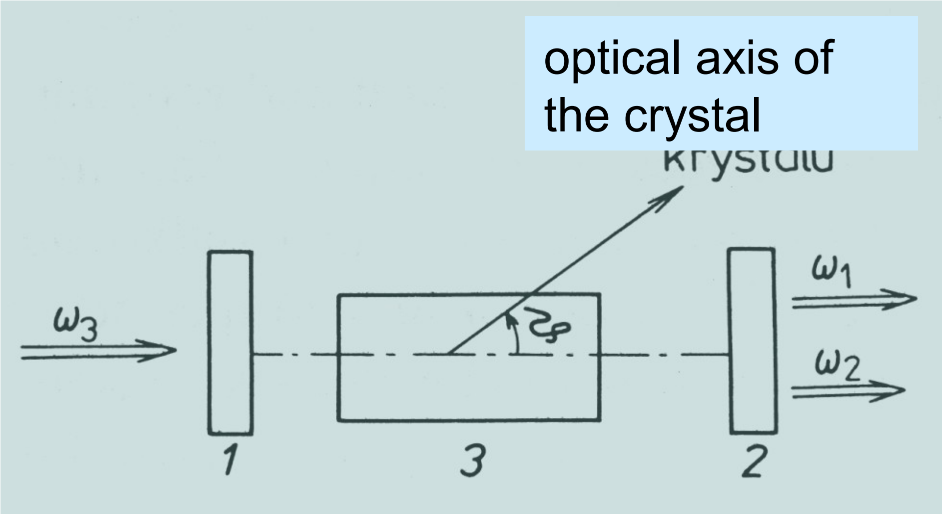
Optical Parametric Oscillator (OPO)

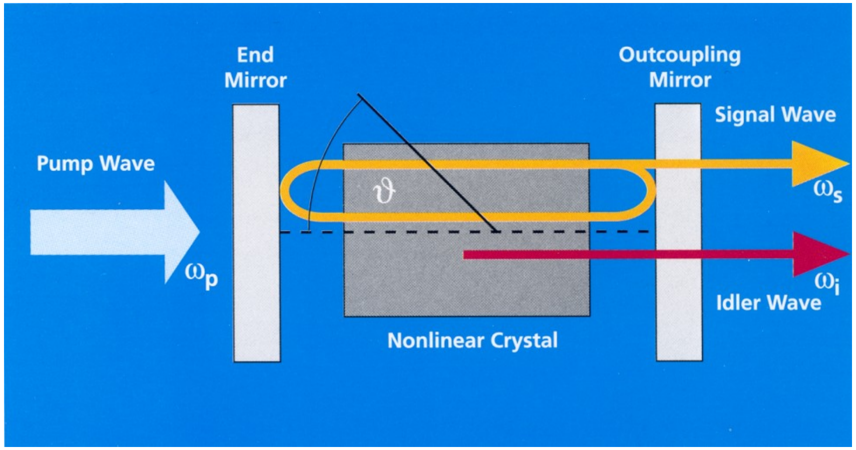
- Based on a coherent decay photon of angular frequency $\omega3$ two photons whose angular frequencies $\omega1$ and $\omega2$ (signal wave and idler wave), whereby the following applies:

  $\omega3 = \omega1 + \omega2$

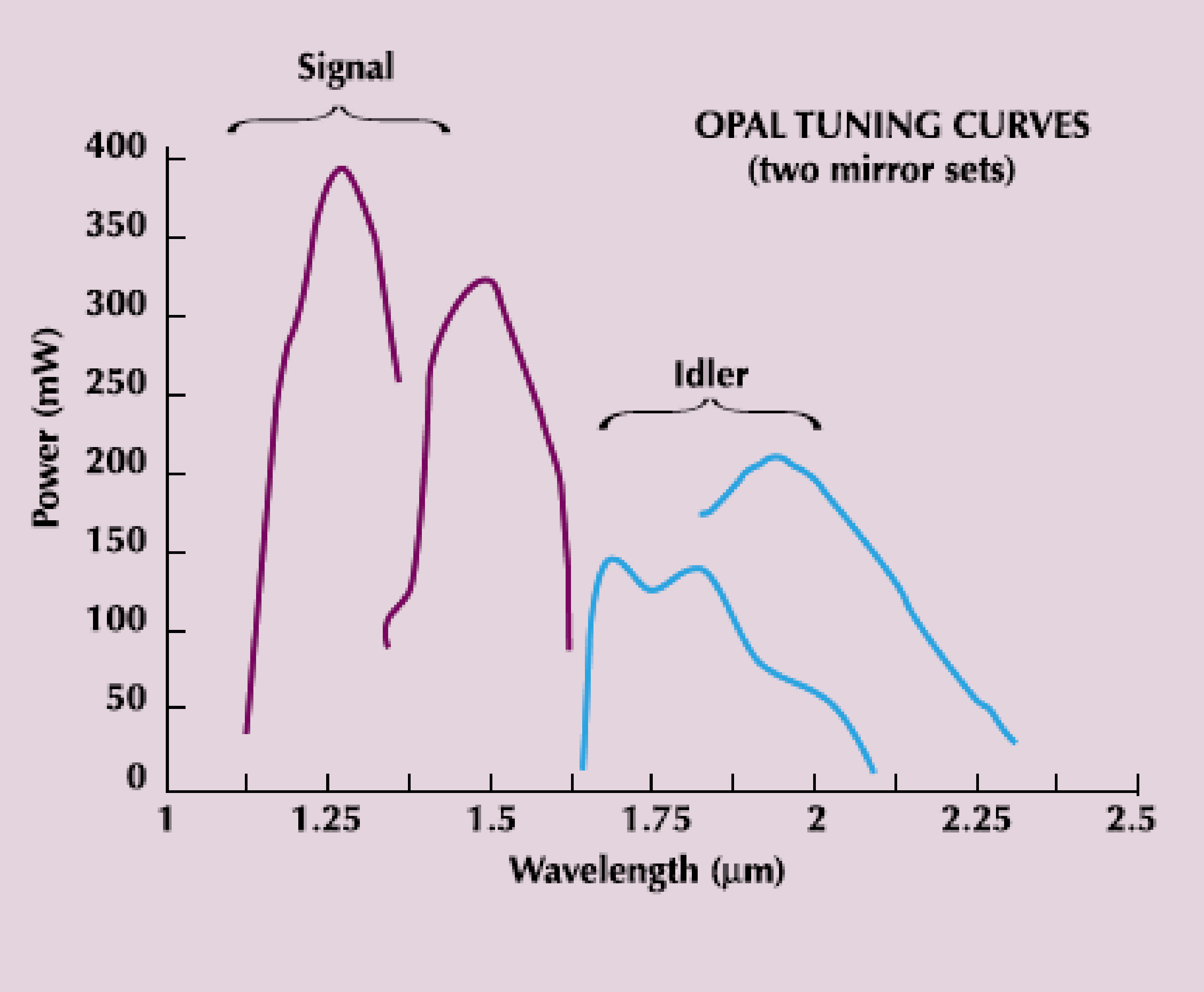
  and ratio

  $\omega1 / \omega2 = f(\upsilon)$

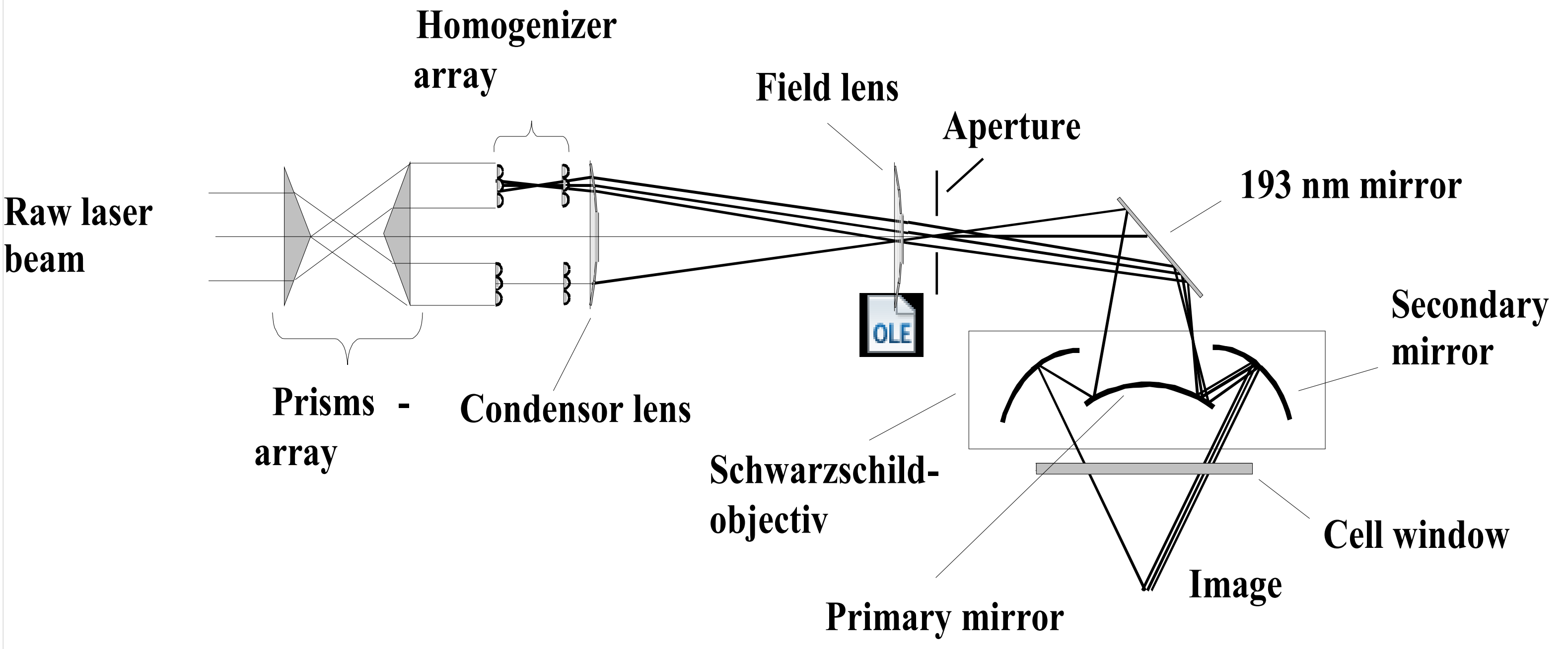

optical axis of the crystal



OPO Spectra Physics



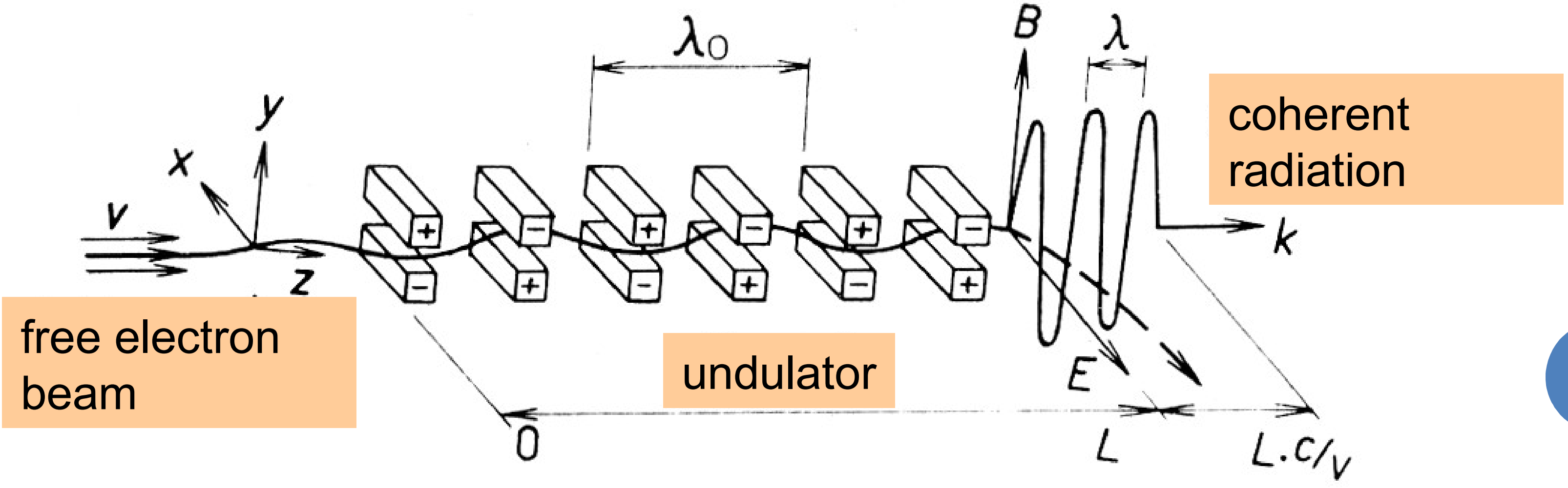
Laser beam homogenization



Free electron laser FEL

The active environment is relativistic electrons passing through the periodic magnetic field. Electrons emit electromagnetic radiation as they move along curved orbits with wavelength:
(γ<< λ0, γ is the so-called relativistic factor):

$$\lambda = \lambda_0\left(\frac{c}{v} - 1\right) = \frac{\lambda_0}{2\gamma^2} \qquad \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$



coherent radiation

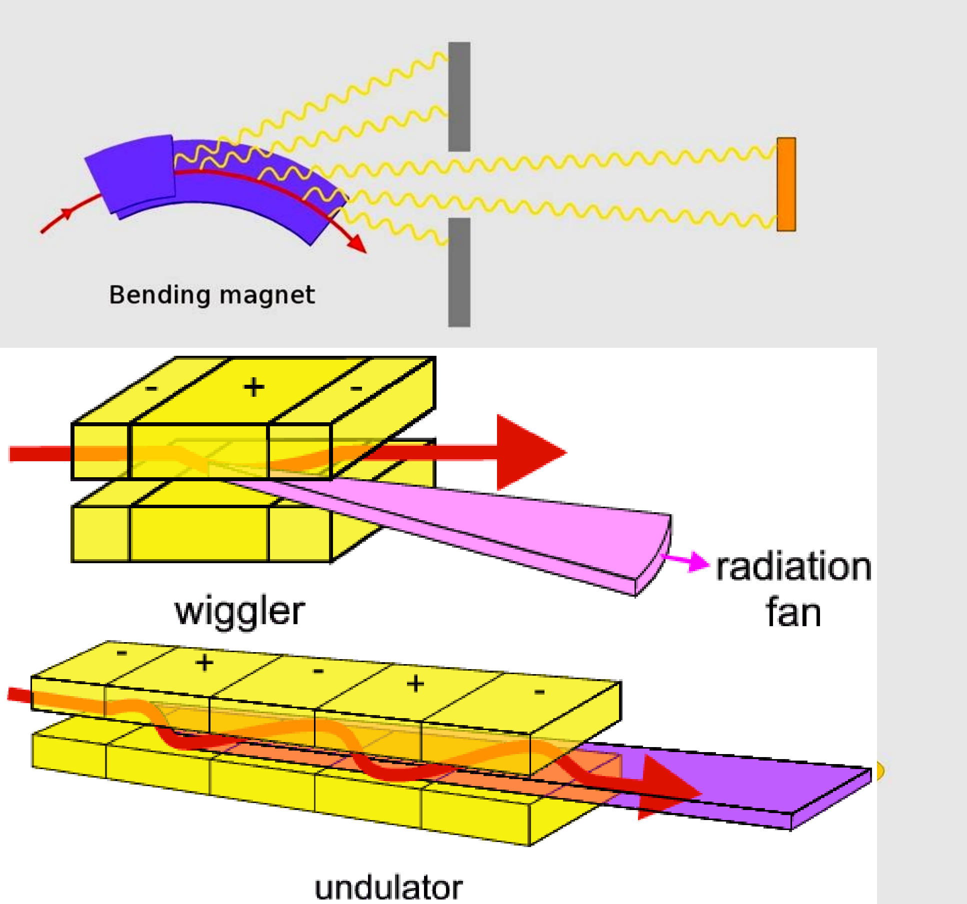
free electron beam

undulator

Spectral brilliance

- For characterization of high-intensity sources (mainly synchrotron) radiation, the term **spectral brilliance** is introduced**,** indicates the number of radiated photons per second per 1 mm2 of the radiation source area, at 1 mrad2 divergence and at 10% of the wavelength range ($\Delta\lambda / \lambda = 0.1$).
- The narrower and more parallel the beam is and the more the photons are concentrated in the narrowest wavelength range, the higher the spectral brilliance.
- This is inversely related to **emittance**, which is essentially the product of the dimension of the radiation source and the radiation divergence.

Synchrotron radiation



Sources of magnetic field

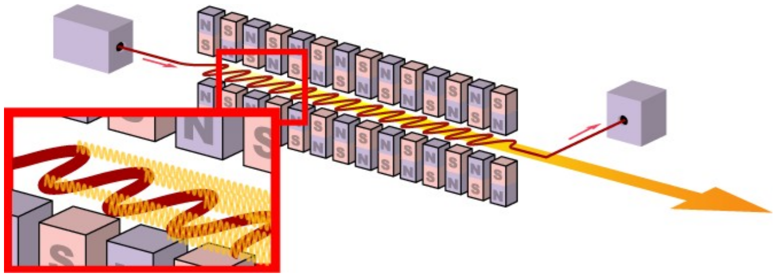
- bending magnets
- undulator
- wigglers

Free electron lasers

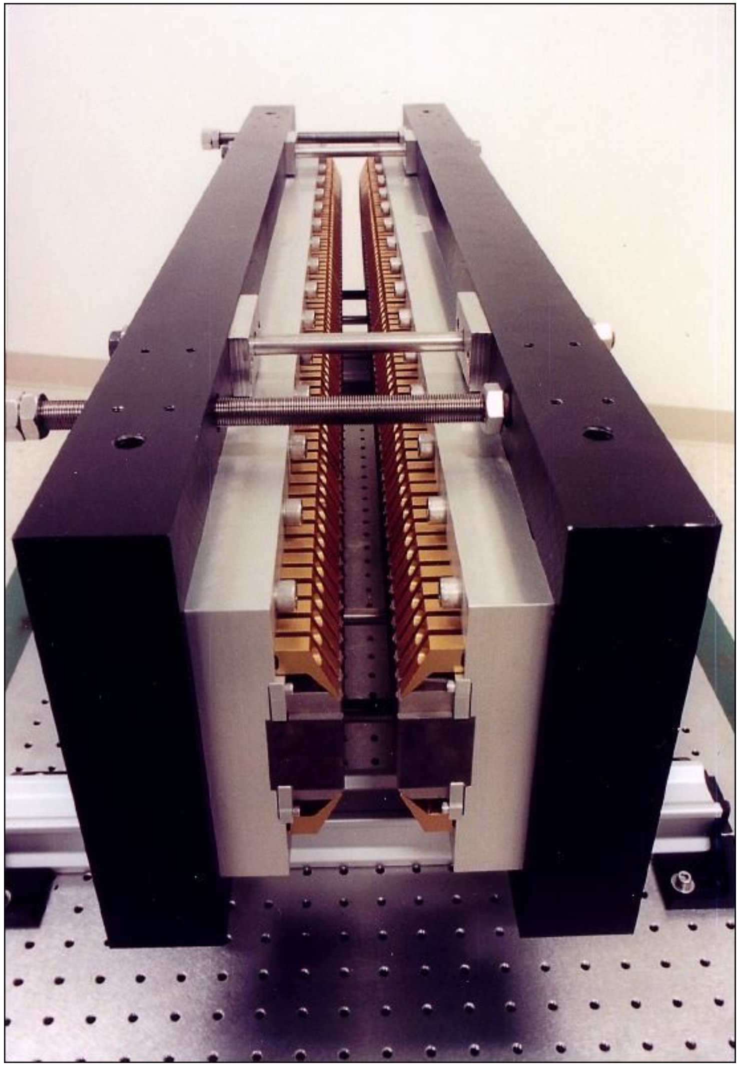
Free Electron Laser

- The **fourth generation** of SZ sources is based on the use of linear accelerators, which allow to reduce emittance and shorten the pulse length. If a short electron burst runs through a sufficiently long undulator, then the electromagnetic wave generated at each location of the undulator proceeds together with the electron beam and interacts with it and results **free electron laser – FEL**. It is characterized by high brilliance, significantly higher than that of a classic undulator, coherence and shortness of pulses reaching tens of fs. A very long linear accelerator is required to accelerate electrons to GeV values.

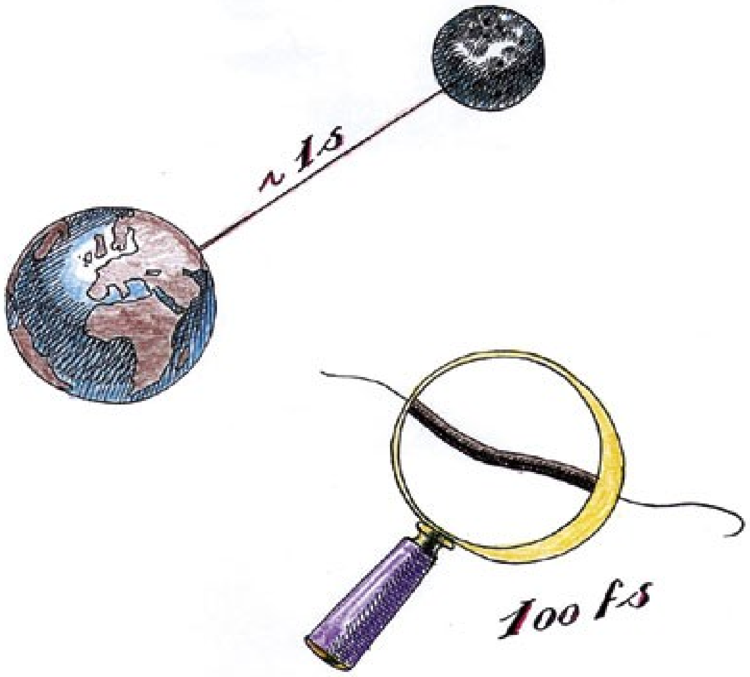
Free Electron Laser



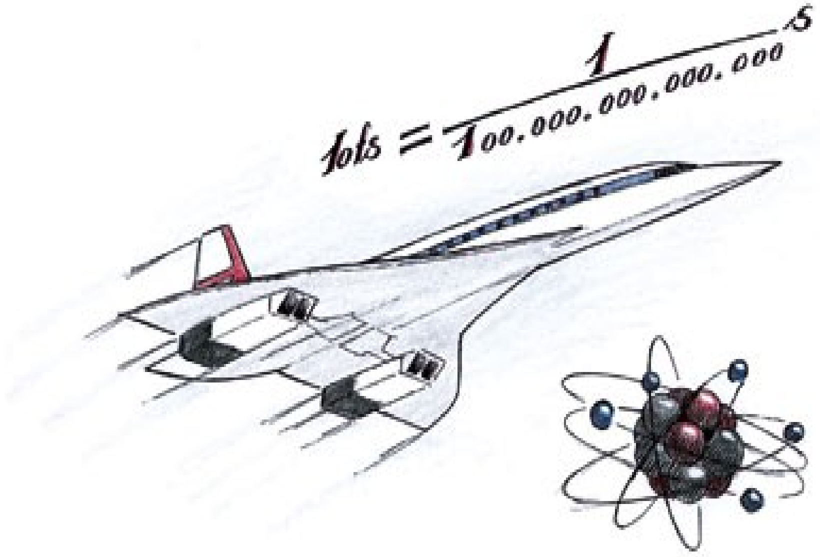
Electron clusters move along a wavy orbit. Charged particles that change their speed (direction enough) emit. For understanding, let's imagine that electrons in a cluster move along a sinusoid along an undulator. If we look at them from the end of this axis, we do not see that they are moving towards us, but we see oscillate cloud of charged particles. The clusters thus generate a coherent X-ray beam. Behind the undullator, the electrons are diverted by a strong magnetic field and the resulting X-ray laser beam continues into the experiment hall



Femtoseconds



Average Earth – Moon distance is around 380,000 km. Light moving at 300,000 km per second will travel this distance in a little more than 1 second...
Within 100 fs however light passes only 30 μm, i.e. less than the thickness of the hair.

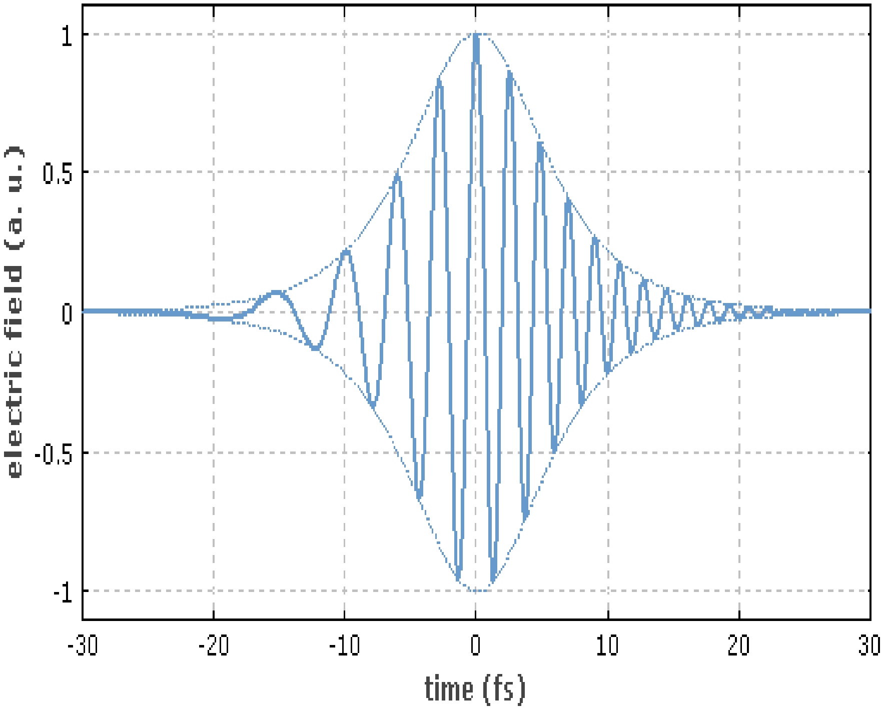


Concorde supersonic flies at approximately 2 Mach (twice the speed of sound in air), or 600 m / sec (2160 km / h). Over a period of 10 fs fly only 6 picometres (6.10-12 m), it is 10 times less than the diameter of the carbon atom.

Chirp

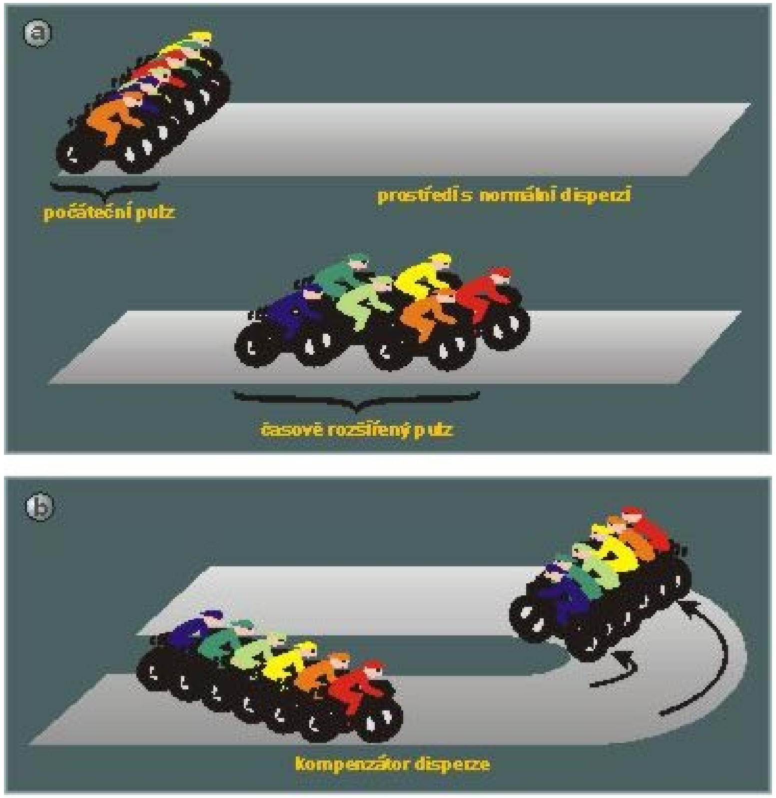
- In the case of pulses of optical radiation, a **Chirp** means a gradual change of frequency during the pulse (increase or decrease). This means that the frequency on the leading edge is different from the closing edge. If such a pulse propagates in a dispersion medium, the rate of propagation of the radiation in the leading edge is less (or greater) than in the closing portion, thereby shortening (or prolonging) the pulse.

Uncertainty relations make it impossible to have a short (~ fs) light pulse in the visible region of the spectrum that is monochromatic



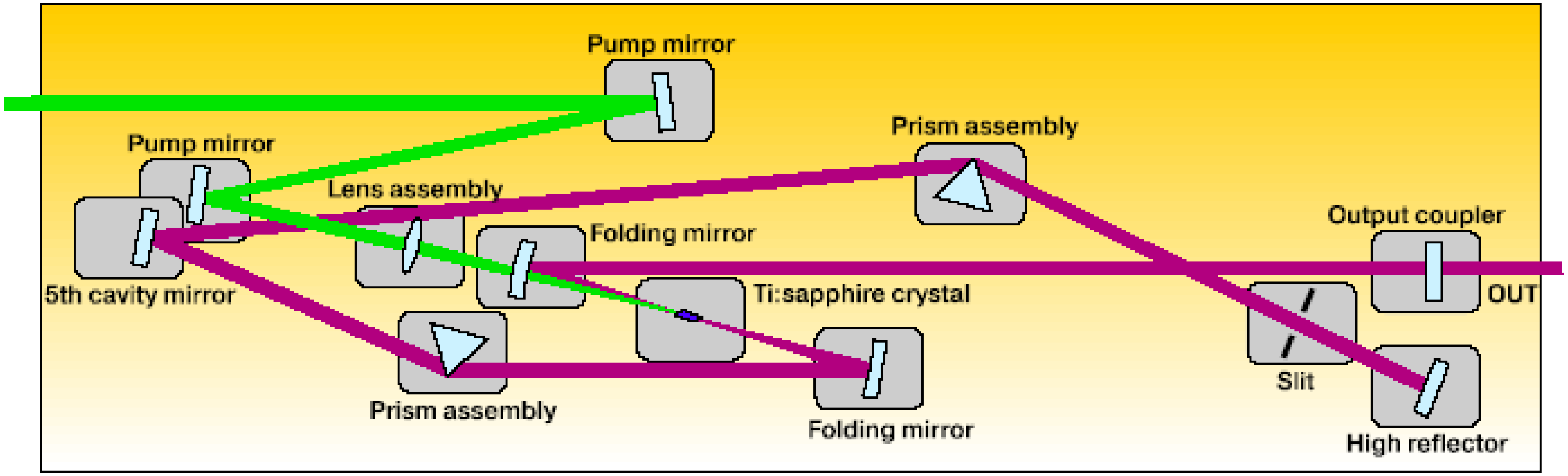
Chirp of femtosecond pulse

- In a dispersed environment, the femtosecond pulse, which has a large frequency range (large wavelength range), is extended by the different dispersion (refractive index, light velocity) of different wavelengths. It is therefore necessary to make a correction with the dispersion compensator to maintain the pulse time profile.



Model TISSA-20: < 20 fs

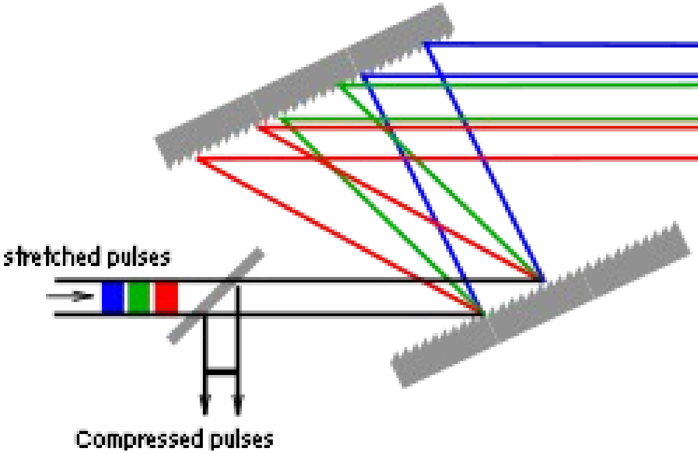
- Stable Kerr-lens mode-locking operation5-mirror compact cavity design.
- Model TISSA-20: Seeding source of broadband femtosecond pulses for Ti:sapphire amplifiers

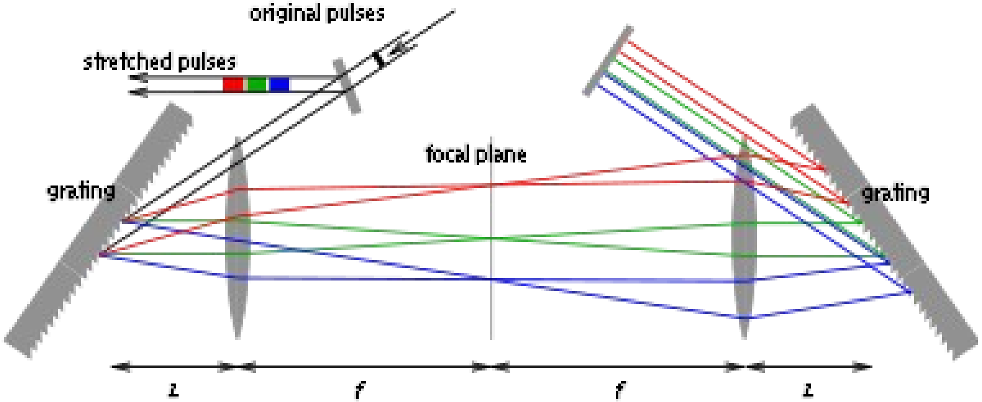


Stretcher and compressor design

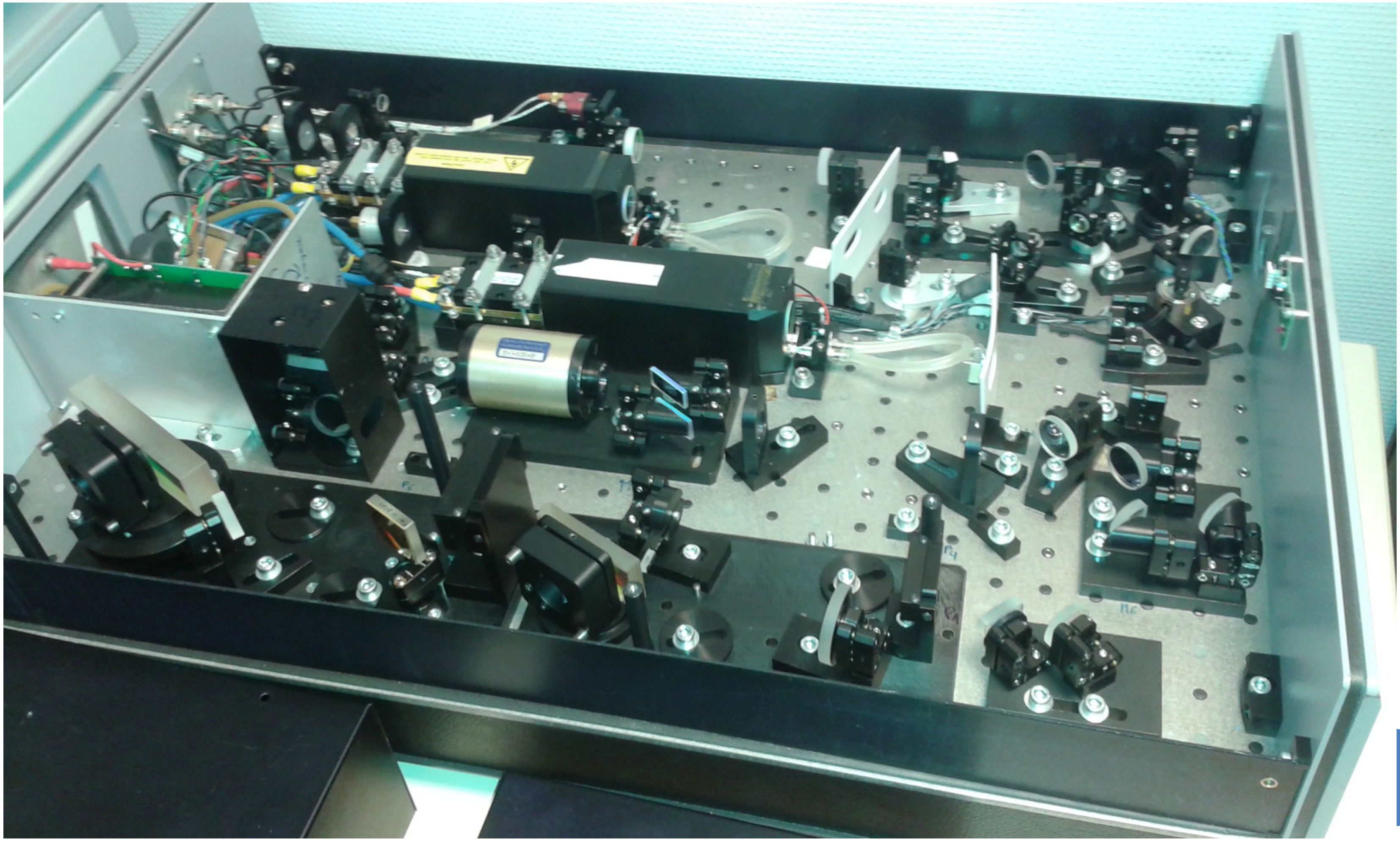
With gratings compressor

With gratings stretcher





Stretcher and compressor design



Amplification of femtosecond pulses with power PW