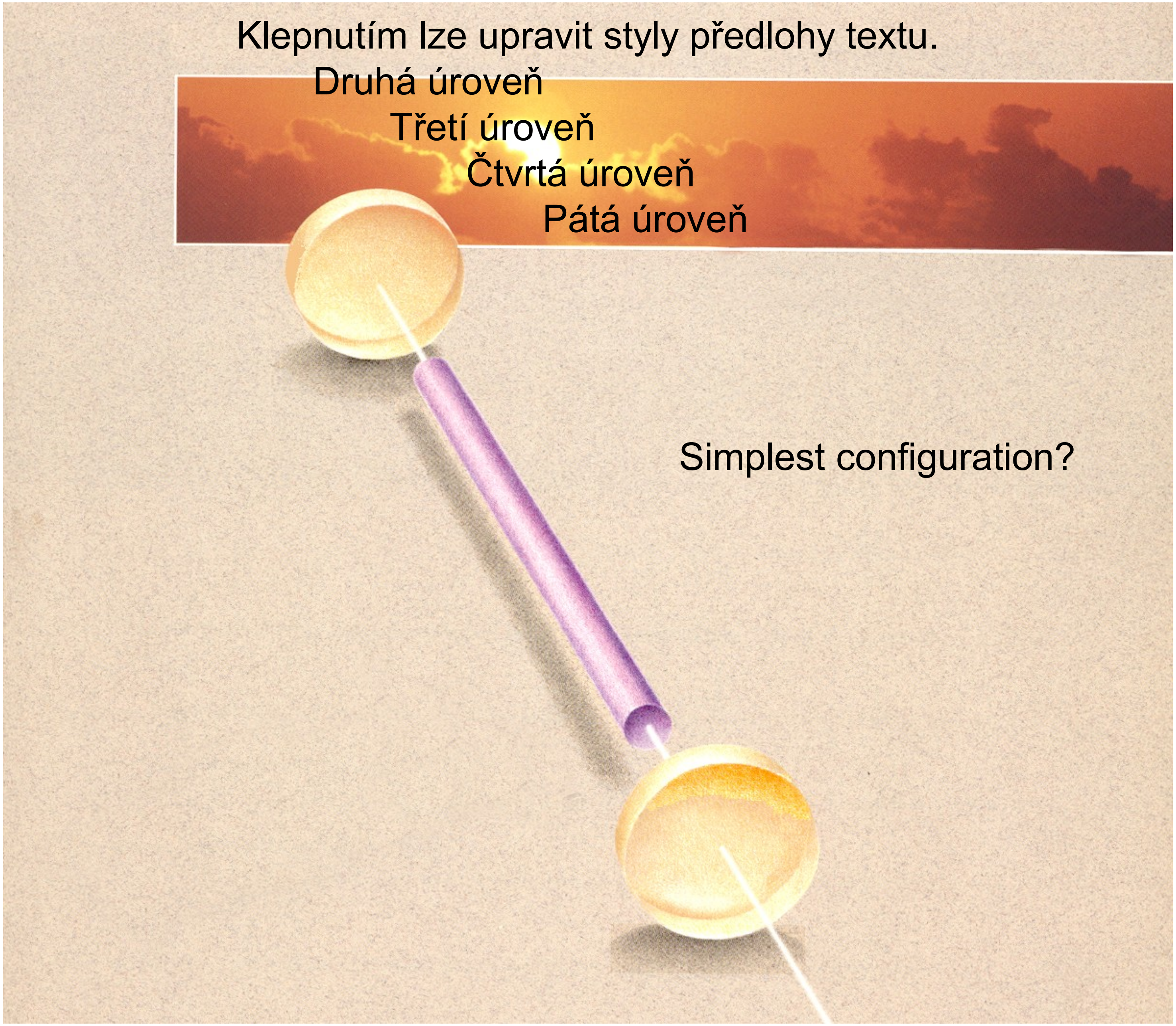
Lasers basics principles

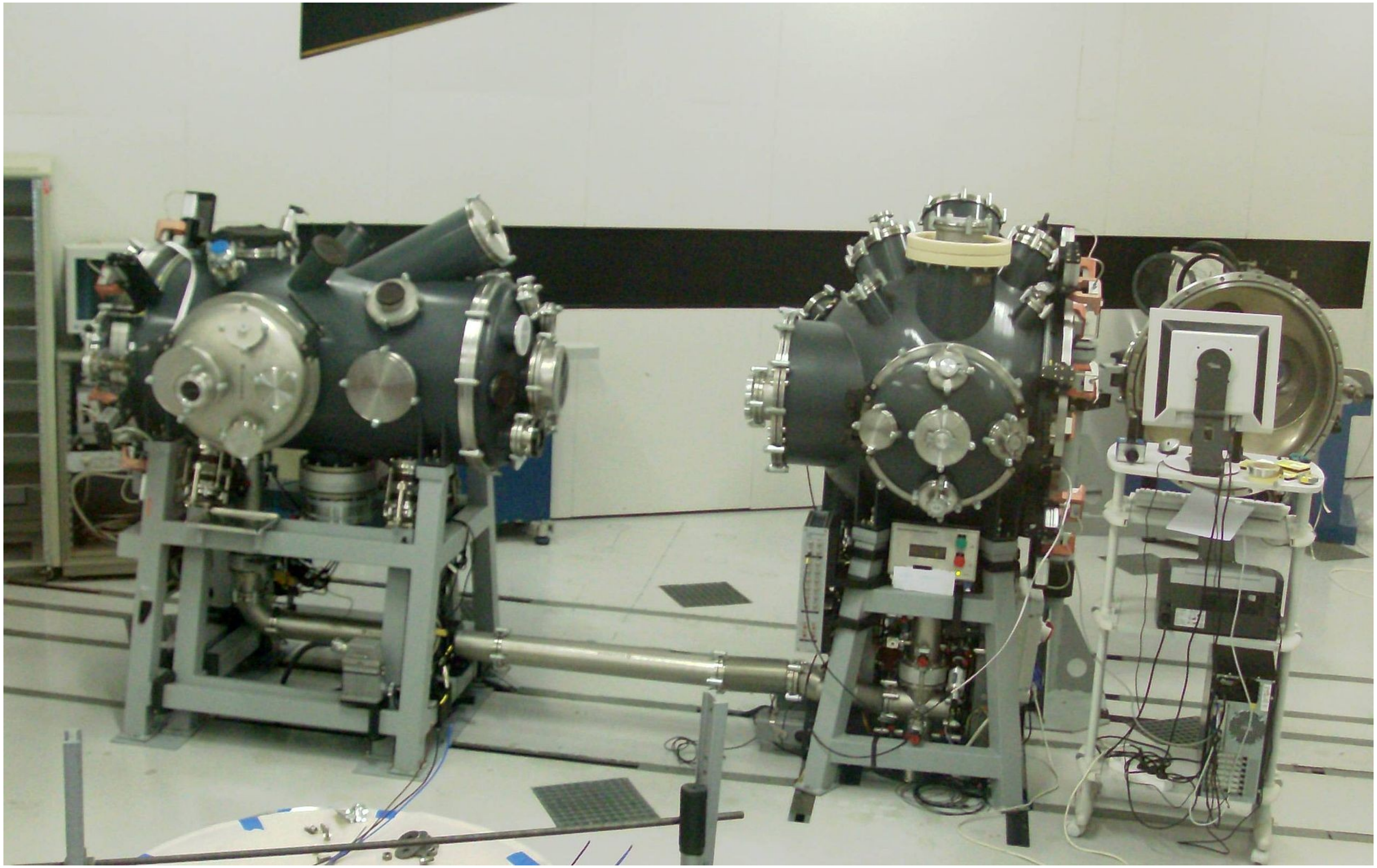
Vítězslav Otruba, Karel Novotný

Klepnutím lze upravit styly předlohy textu.

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



Simplest configuration?



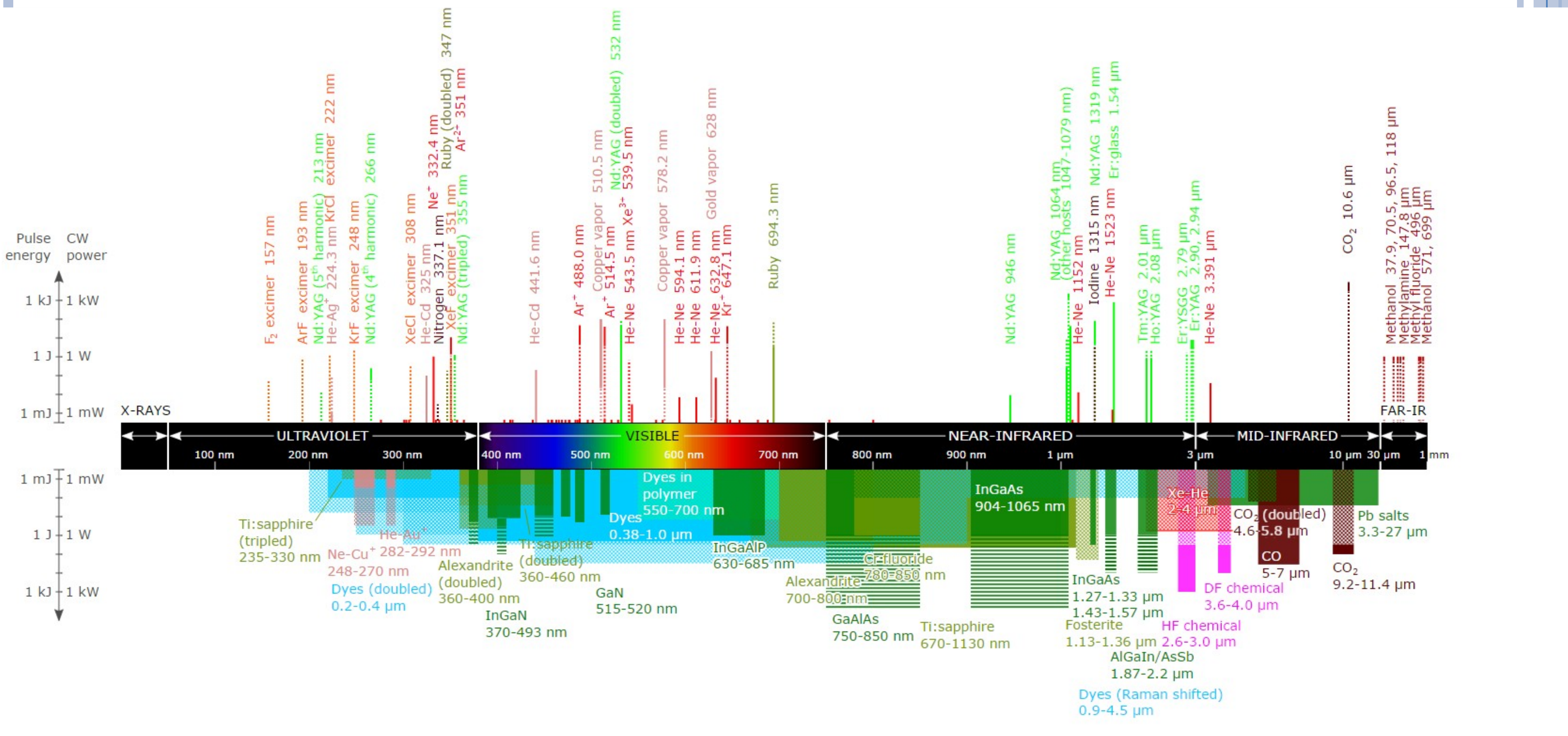
High energetic lasers - PALS Prague Asterix Laser System

The vacuum chambers at the PALS laboratory in Prague, where a 1 kJ pulse creates plasma for X-ray generation

Lasers – Light Amplification by Stimulated Emission of Radiation

- Spectral range 1 mm – 50 nm, (experimentally) X ray range up to 1 nm, extreme experiments up to 0,01 nm – radiation generators especially (XASER)
- For sub millimeter wave range MASERS (Microwave Amplification by Stimulated Emission of Radiation) - mainly as low noise radio signal amplifiers

Commercially available – VUV – VIS – MID IR



Properties of laser radiation

- Emissions of elementary oscillators(atoms, molecules…) narrow beam– spatial energy concentration
- Δλ can be very small– spectral concentration of energy
- Synchronous operation of elementary oscillators– time concentration of energy
- Coherence length up to tens (in vacuum up to thousands) kilometers

6

Types of lasers by:

• emission wavelengths

• time mode of operation - continuous (cw) or pulse

• type of excitation – optical excited lasers, electric discharge, chemical, mechanical (particle collisions), injection of charge carriers, …

• type of active medium - solid, liquid (dye), gas, ion, excimer, semiconductor (diode),…

• pulse duration (nanosecond, picosecond, femtosecond, ...) - the shorter pulse duration means higher the **Peak power** at the same **Average Power**

Types of lasers

Properties of <u>Active laser medium</u> (gain medium, lasing medium)

Excitation of atoms up to <u>metastable state</u> →

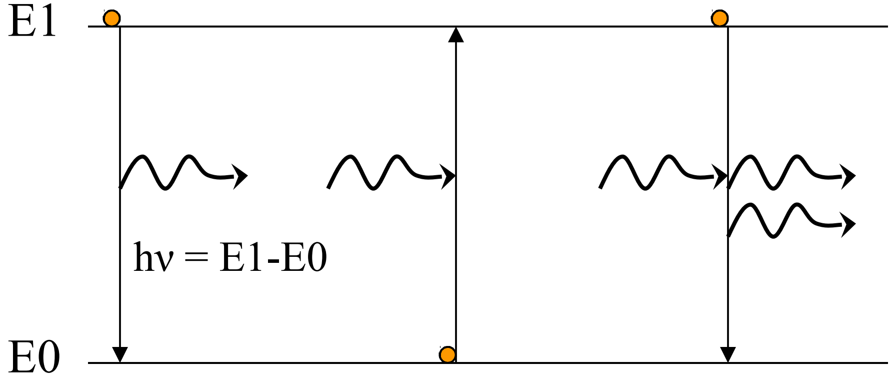
- By collisions between two kinds of atoms (He-Ne, CO2)
- Optical excitation – pumping (ruby, neodymium glass)
- Excitation in the chemical reaction (eximers)
- By electric current (semiconductors,GaAs)

and other ways

Light output of lasers:

1. **Continuous laser** up to tens of mW
2. **Pulse laser** with an average power of 10 mW can have parameters**:**
   - pulse duration = 1 ns,
   - pulse energy = 1 mJ,
   - pulse power = 1 MW
   - repetition rate = 10 Hz

Radiation Processes



spontaneous emission | absorption | stimulated emission

A ~ ΔE2 ~ λ-2 (transition probability)

Radiation intensity : I(ν)=Nu·A·hν

Strong transitions :
E1 (electric dipole)

A~108 s-1 for neutrals

Weak transitions:

M1 (magnetic dipole),
E2 (electric quadrupole),
some E1

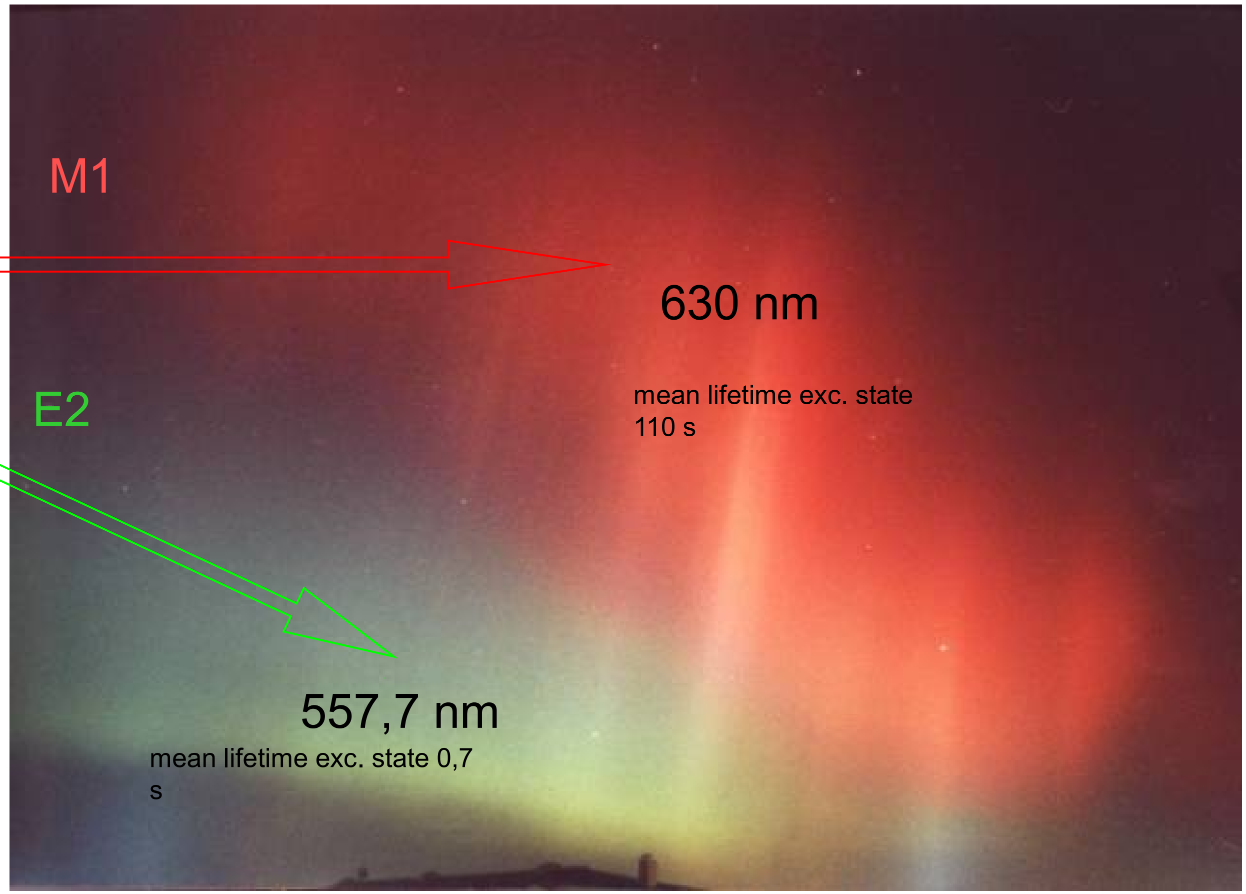
A ~1-100 s-1 for neutrals

Radiative Processes cont'd

O I lines:

3P1-1D2
3P2-1D2

1D2-1S0



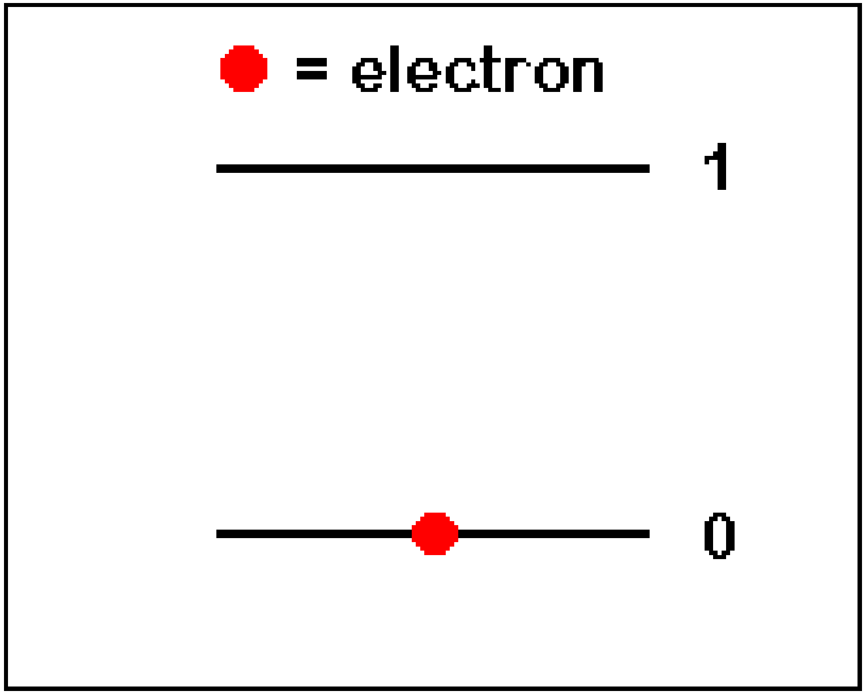
spontaneous emissions

- Probability of photon absorption :

  $w01=n0\rho(\nu)B01$

- Probability of spontaneous emissions :

  $w10=n1A10$



$\rho(\nu)$ – spectral density of radiation with frequency ν

B01 – Einstein coefficient of absorption

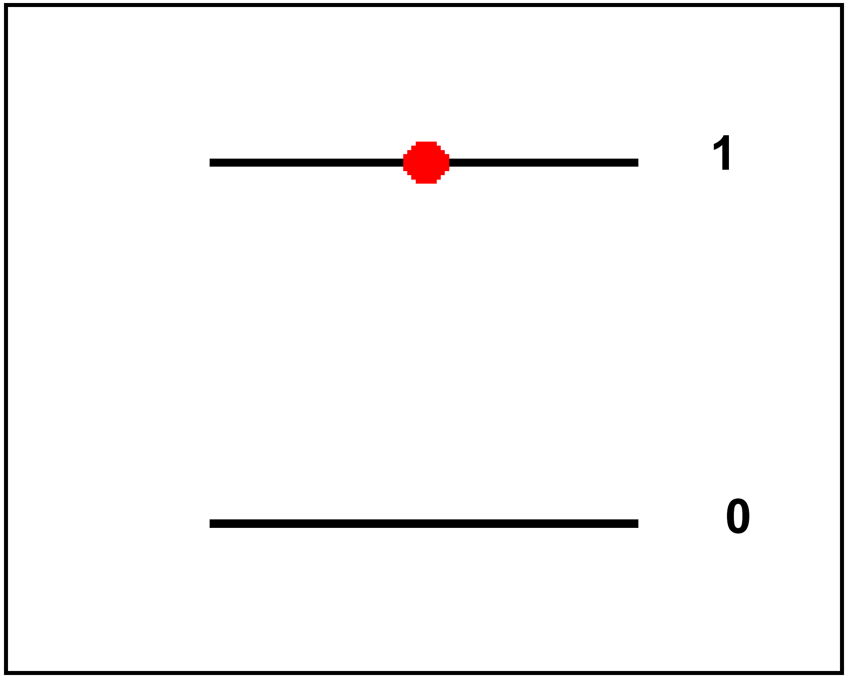
A10 – Einstein coefficient of spontaneous emission

Stimulated emission

- Probability of stimulated emission :

  $w10=n1\rho(\nu)B10$

B10 – – Einstein coefficient of stimulated emission



- Process of interaction with radiation :

  $n0\rho(\nu)B01=$

  $n1\rho(\nu)B10 +n1A10$

Interaction with radiation

Two-level model in thermodynamic equilibrium :

$$n_0 \rho(\nu) B_{01} = n_1 \rho(\nu) B_{10} + n_1 A_{10}$$

From the equation we express ρ(v):

$$\rho(\nu) = \frac{n_1 A_{10}}{n_0 B_{01} - n_1 B_{10}} = \frac{A_{10}}{\dfrac{n_0}{n_1} B_{01} - B_{10}}$$

Boltzmann distribution in TD equilibrium (exponential decrease in level occupation with increasing energy):

$$\frac{n_0}{n_1} = \exp\left(\frac{E_1 - E_0}{kT}\right) = \exp\left(\frac{h\nu}{kT}\right) \qquad [1]$$

Relation between Einstein coefficients

Substituting the Boltzmann distribution [1] into the previous equation for volume density of radiation we get:

$$\rho(\nu) = \frac{A_{10}}{B_{10}} \frac{1}{\frac{B_{01}}{B_{10}} \exp\left(\frac{h\nu}{kT}\right) - 1}$$

For the spectral density of radiation we can use Planck relationship:

$$\rho(\nu) = \frac{4h\nu^3}{c^3} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

By combining the equations, it is possible to find the relationship between the Einstein coefficients:

$$B_{10} = B_{01} = B \quad \text{and} \quad A_{10} = \frac{4h\nu^3}{c^3} B_{10}$$

What is the relative number of acts of stimulated and spontaneous emission per unit of time?

$$R = \frac{\text{The number of stimulated emissions per second}}{\text{The number of spontaneous emissions per second}}$$

wavelength	wavenumber (cm-1)	frequency (Hz)	R	
			$T = 300$ K	$T = 1000$ K
1 mm	10	$3{,}0.10^{11}$	20,3	69,0
25 μm	400	$1{,}2.10^{13}$	0,17	1,29
2,5 μm	4000	$1{,}2.10^{14}$	5.10^{-9}	3.10^{-3}
780 nm	12820	$3{,}84.10^{14}$	2.10^{-27}	1.10^{-8}
500 nm	20000	$6{,}00.10^{14}$	2.10^{-42}	3.10^{-13}
390 nm	25641	$7{,}69.10^{14}$	4.10^{-54}	1.10^{-16}

Inverse population

- The Einstein coefficients for stimulated emission and absorption are equal: **$B_{01}=B_{10}=B$**
- For absorption:

  $d\Phi_A = h\nu n_0 B \rho(\nu) dt$

- For stimulated emission:

  $d\Phi_E = h\nu n_1 B \rho(\nu) dt$

- Total radiant flux change:

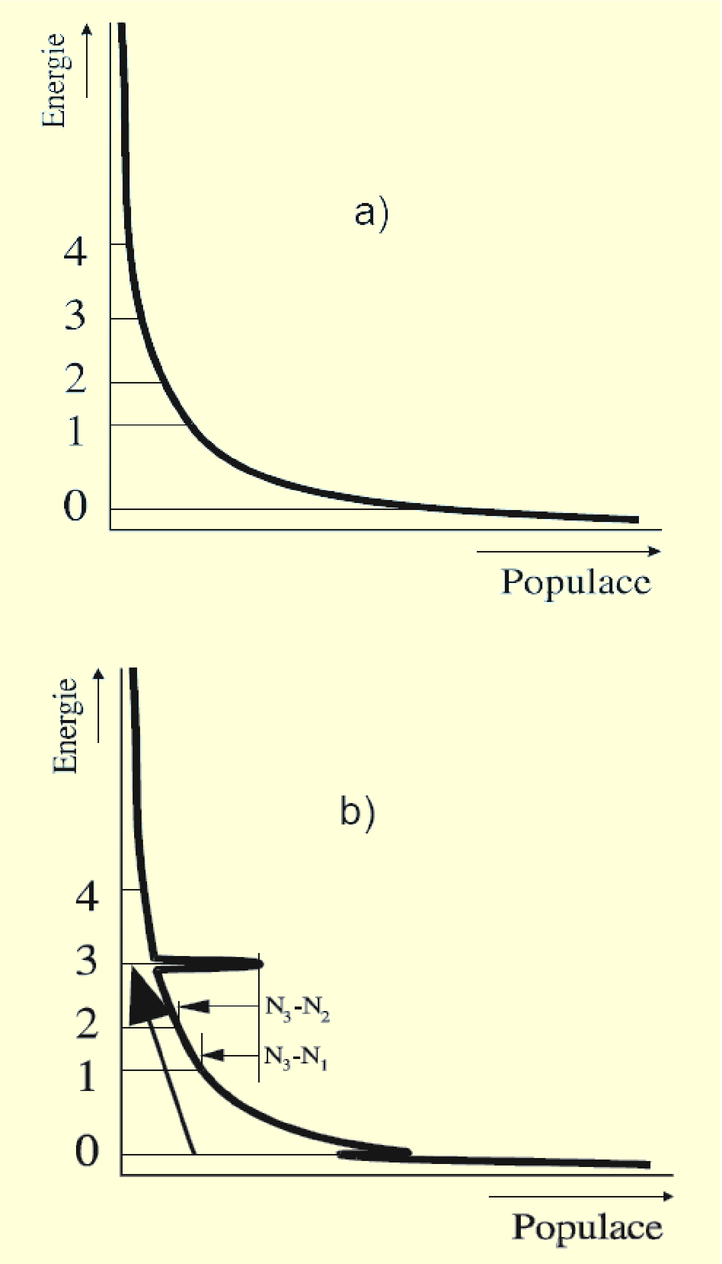
  $d\Phi/dt = h\nu (n_1 - n_0) B$

- Condition for amplification of radiation:

  $n_1 - n_0 > 0$, tj. inverse population

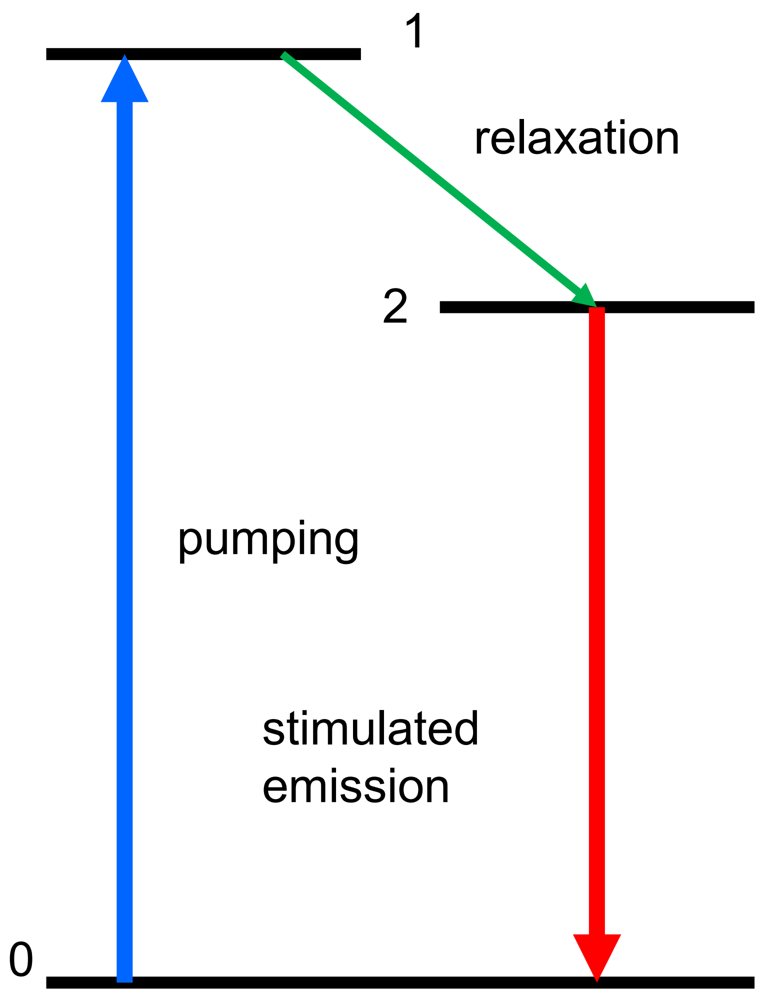
Inverse population

- The normal population distribution is shown in Figure a).
- In order to create an active environment, it is necessary to intervene in the system in order to change the distribution of the energy level occupation in the way shown in Figure b).
- The process is usually referred to as laser excitation or pumping. The basic method is optical excitation.

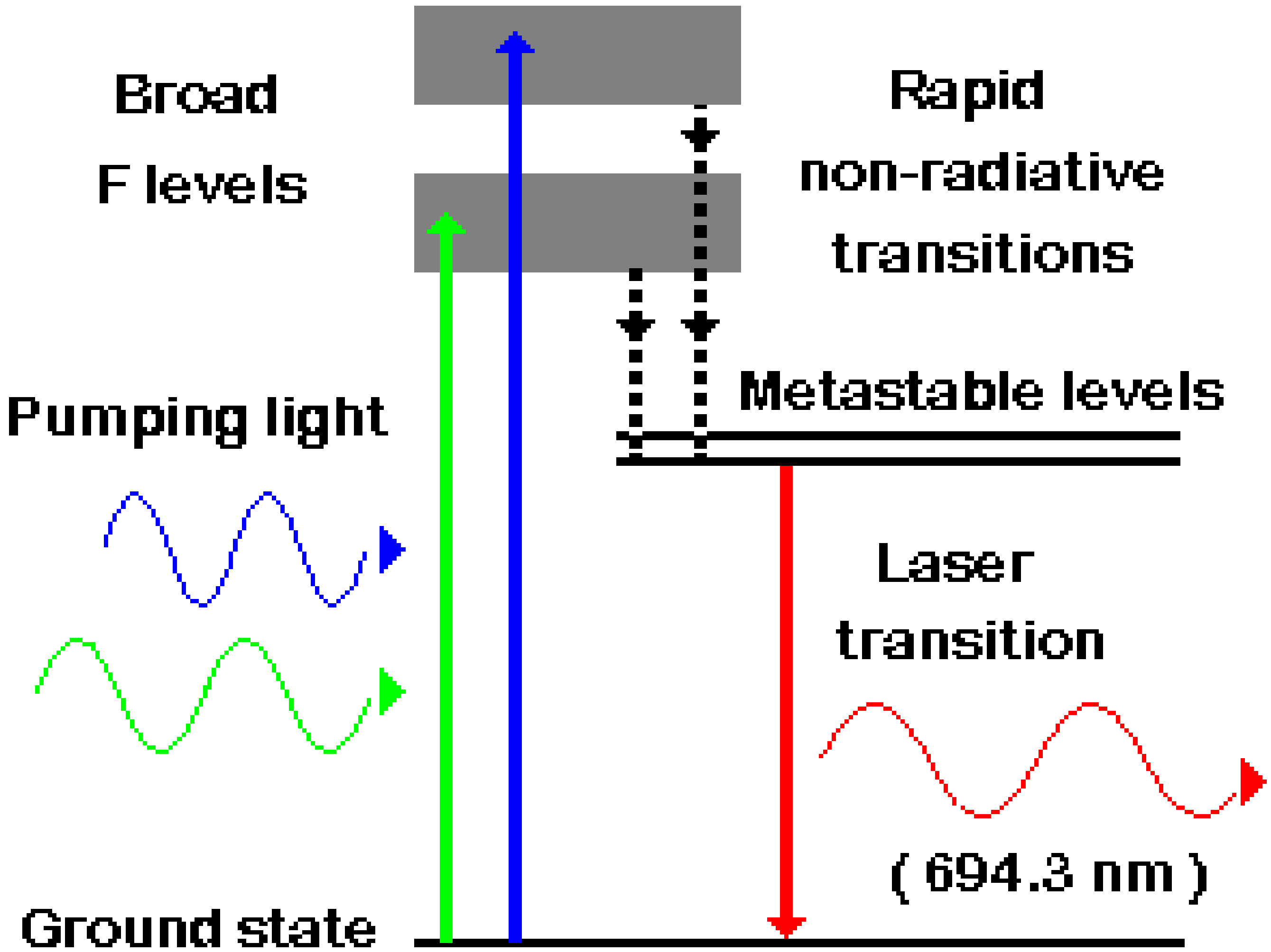


Three-level system

- Application: ruby laser
- Level 2 is metastable
- The disadvantage is low efficiency - for reach the inverse population at least 50% of the particles have to be brought to level 2

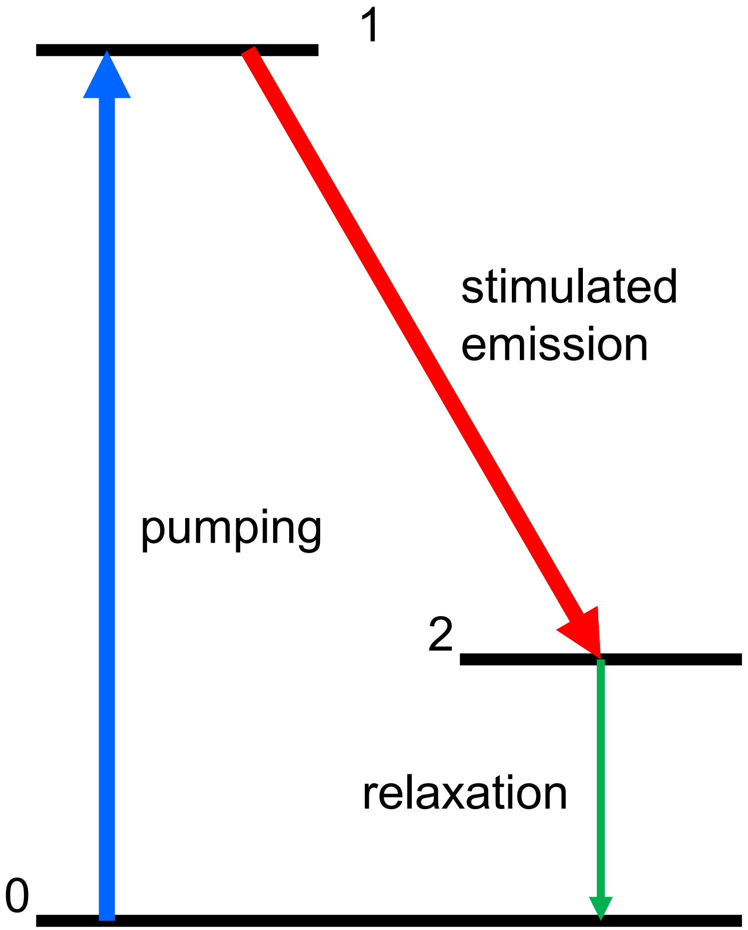


Energy diagram of a ruby laser



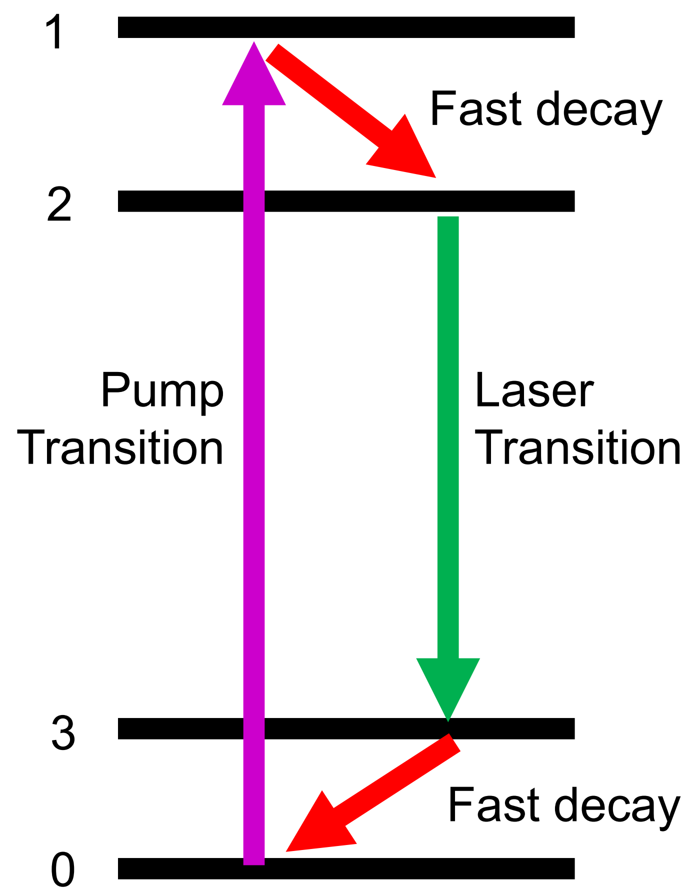
Three-level system

- Modified three - level system with excitation to metastable level 1.

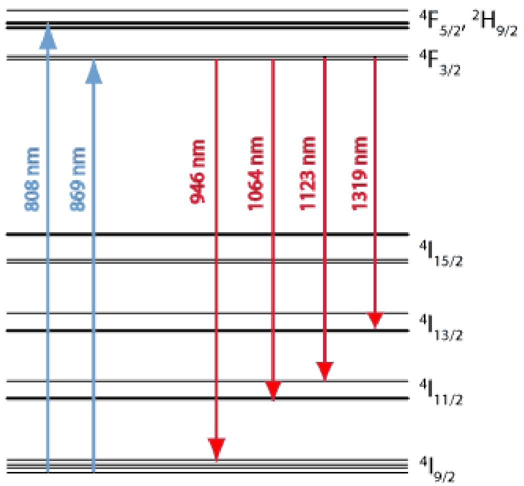


Four-level system

- Example - laser Nd: YAG
- High efficiency
- An inverse population must only be reached between levels 2 and 3

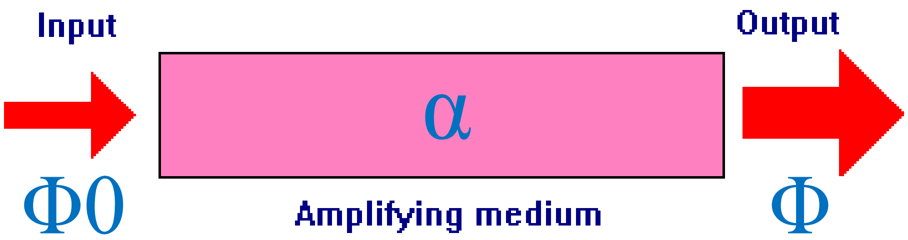


21



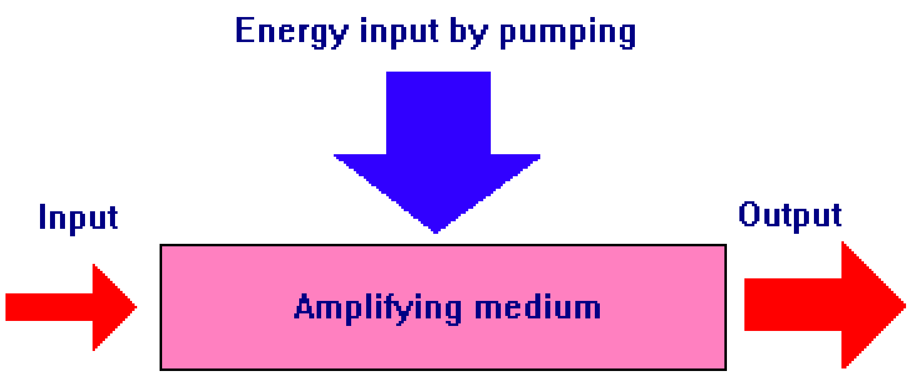
Radiation amplification - quantum amplifier

- Active environment amplifies the incoming radiation:



$$\Phi=\Phi_0 \exp[-l(\alpha+\beta)]$$

α - absorption coefficient ($\alpha<0$)

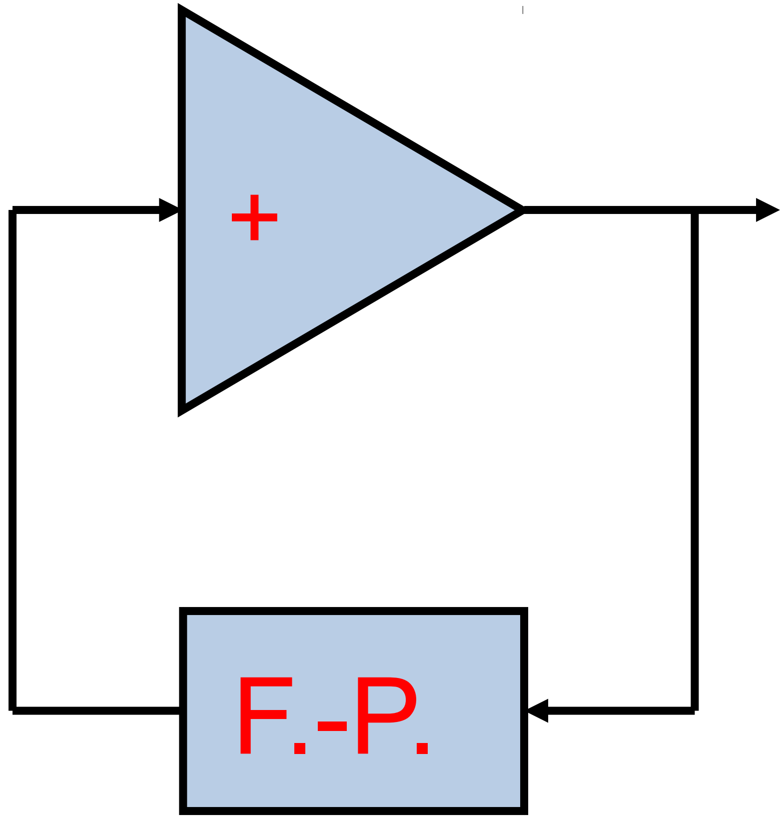


β - losses ($\beta>0$)

l - length of amplifying medium

Generation of radiation

- By introducing positive feedback from the output to the input of the amplifier we get an oscillator whose frequency is given by the amplifier and the feedback circuit, usually realized by a Fabry-Perot resonator

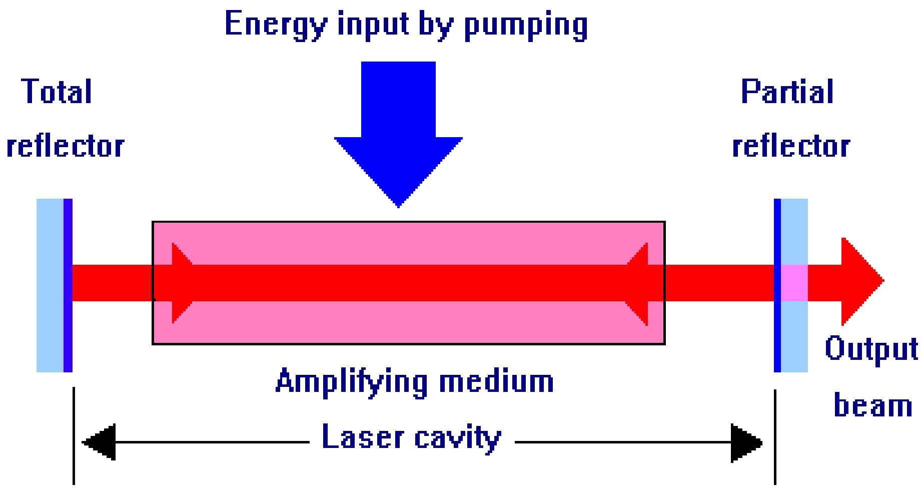


Laser radiation generation

- Feedback is usually realized by a Fabry-Perot resonator.
- For short pulse generation, the amplifier frequency bandwidth must be at least:
- $\Delta f \cong 1/(2\tau)$

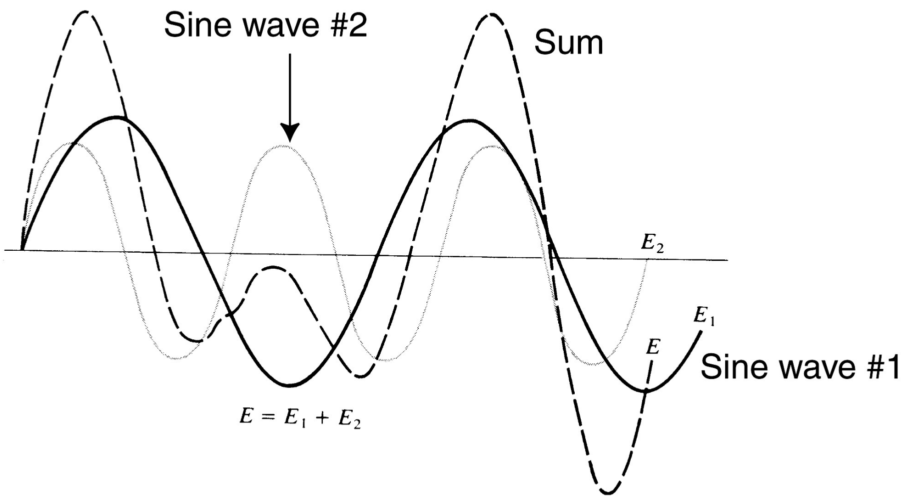
where τ is the pulse width

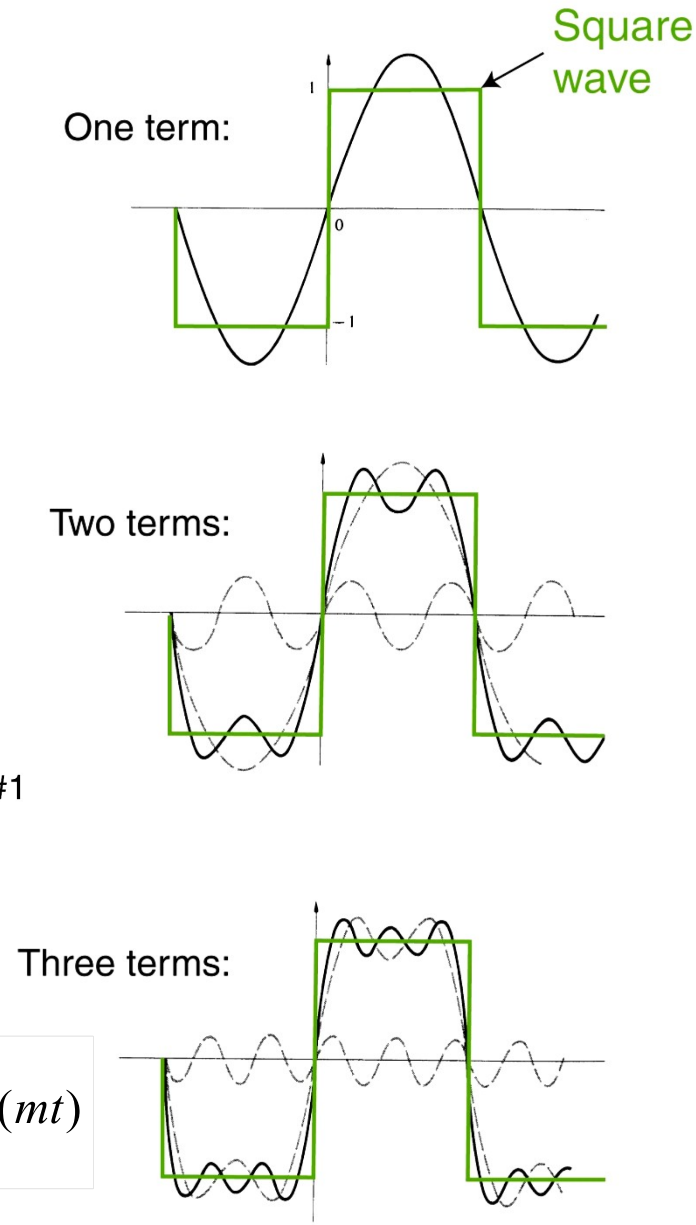
(polychromaticity of short pulses)



Fourier decomposing functions

Anharmonic waves are sums of sinusoids.

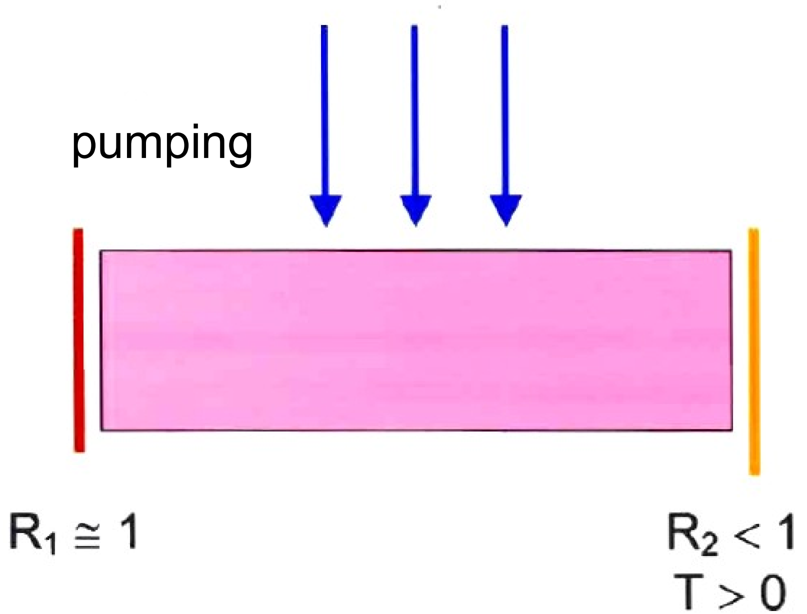




$$f(t) = \frac{1}{\pi}\sum_{m=0}^{\infty} F_m \cos(mt) + \frac{1}{\pi}\sum_{m=0}^{\infty} F'_m \sin(mt)$$

Conditions for radiation generation

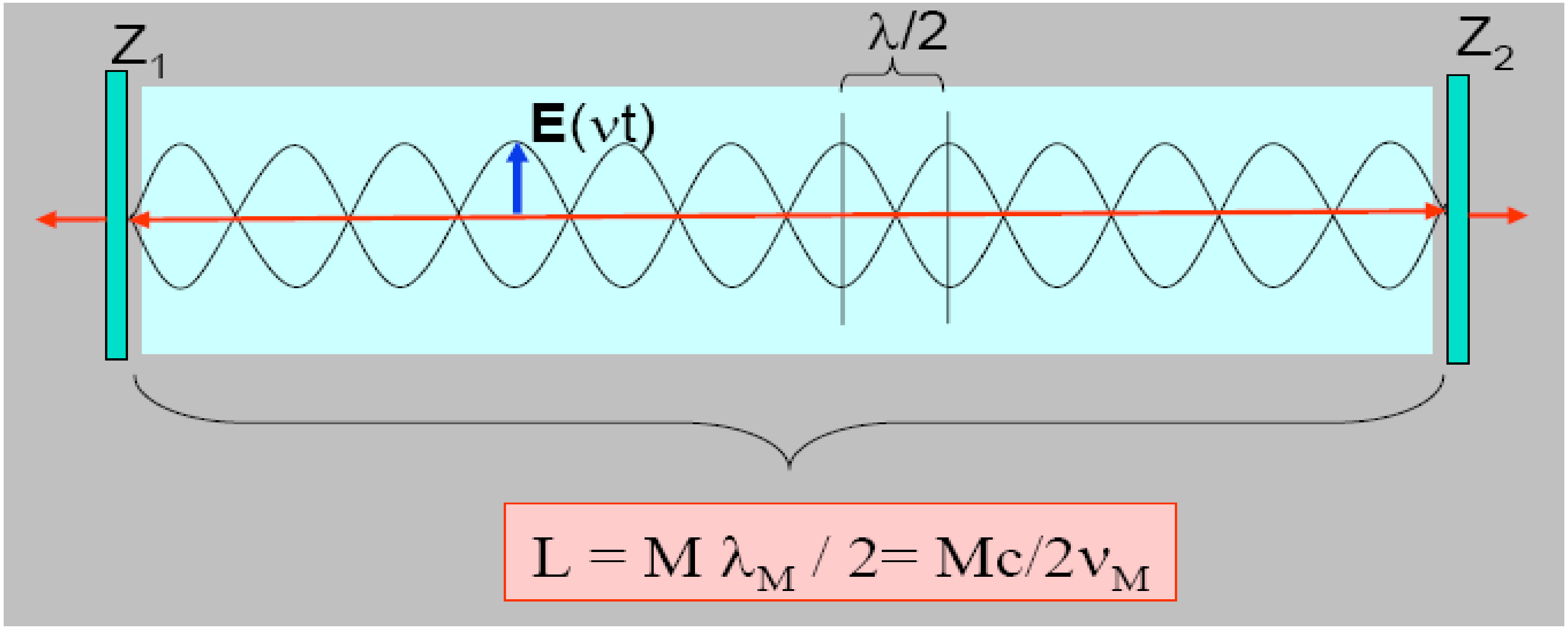
- The reflectance of the mirrors shall be chosen with regard to the amplification of the active environment so that the losses do not exceed the amplification of the active environment G:



$$(R_1R_2)^{1/2}\,G > 1$$

- $R1R2\exp[-2l(\alpha+\beta)]\geq 1$

Optical resonator



The length of resonator L is M multiple of half-wave (M is an integer). The length L corresponds to given resonator frequencies **νM (longitudinal laser modes).** Inside the resonator is a **standing wave** of electric field E with frequency **$\nu M = c/\lambda M$**

Fabry-Perot etalon

- Quality of resonator Q

(QFP~108-109)

$$Q = \frac{\omega_0 E_m}{P_z} = \frac{2\pi\nu_0 E_m}{P_z} \qquad P_z = -\frac{dE_m}{dt}$$

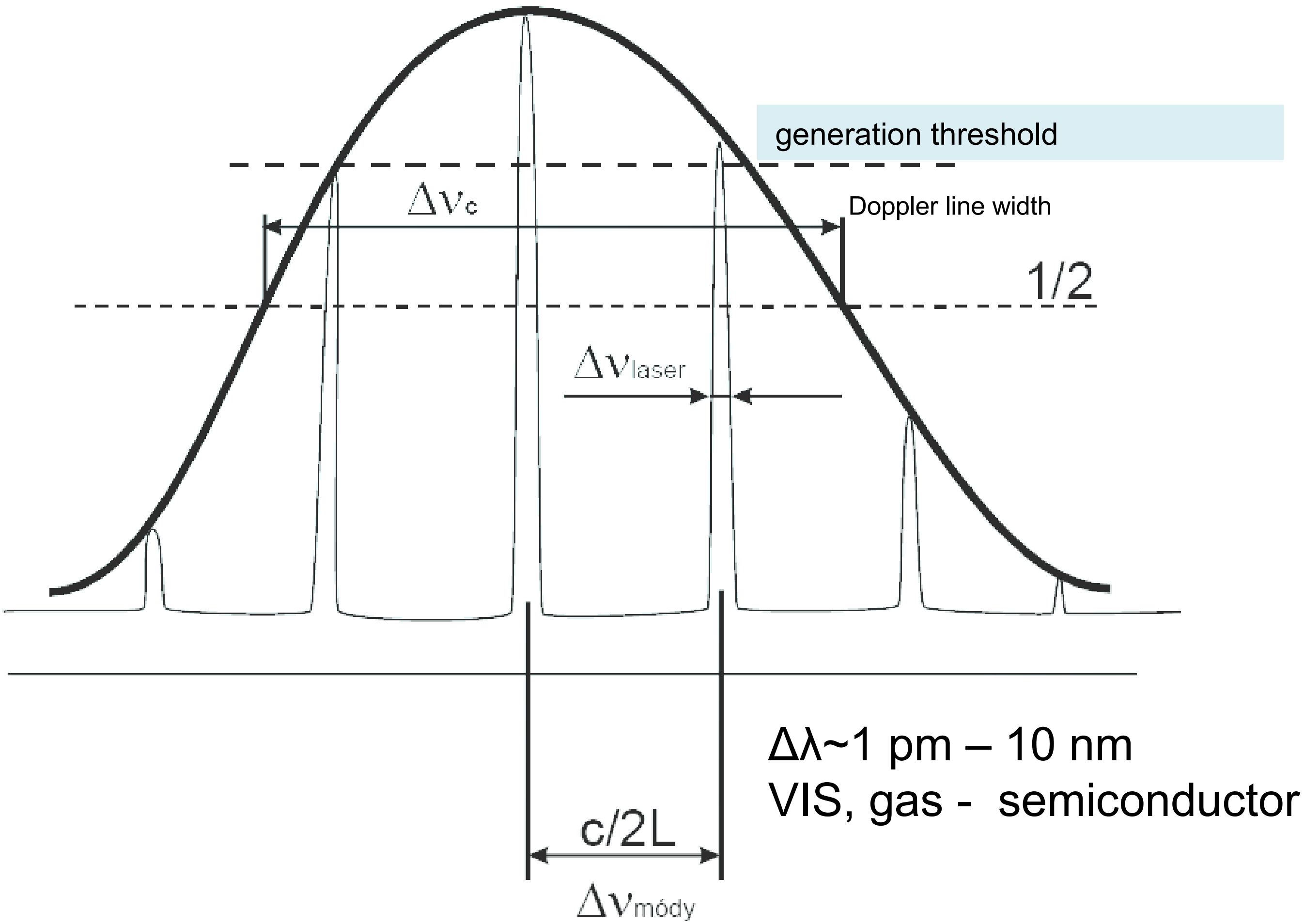
Em- energy of the given mode

Pz- power dissipation

ω0- angular frequency of oscillator

ω0 = 2πv0 =2π/T0 [s-1]

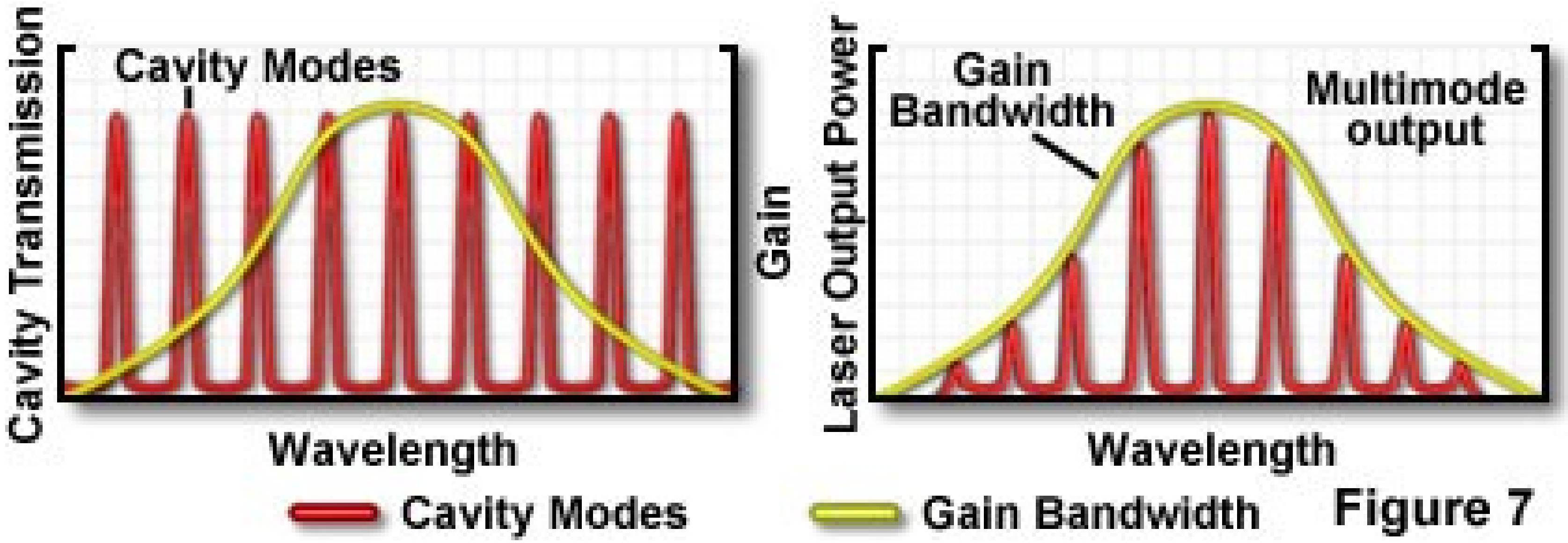
Spectral line width and laser modes



Δλ~1 pm – 10 nm
VIS, gas - semiconductor

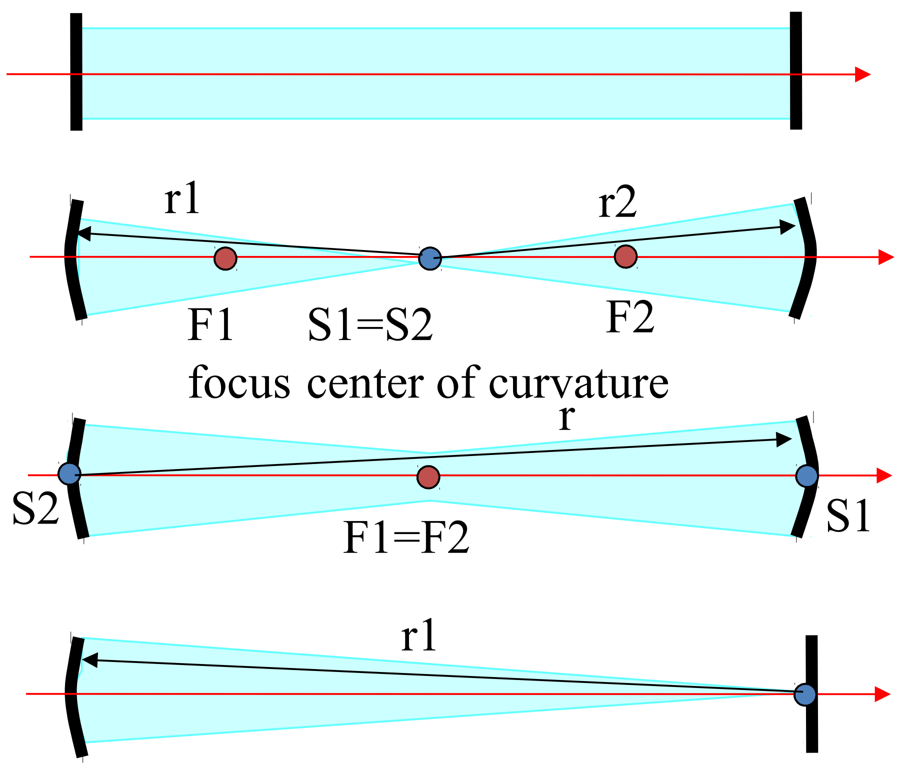
The figure shows the individual resonances basic longitudinal mode.

Resonant modes and bandwidth gain of the active medium



Optical resonators

Volume of the optical (electric) field in resonator



Planparallel : r1 = r2 = ∞

Concentric : r1 = r2 = L/2

Confocal : r1 = r2 = r = L/4

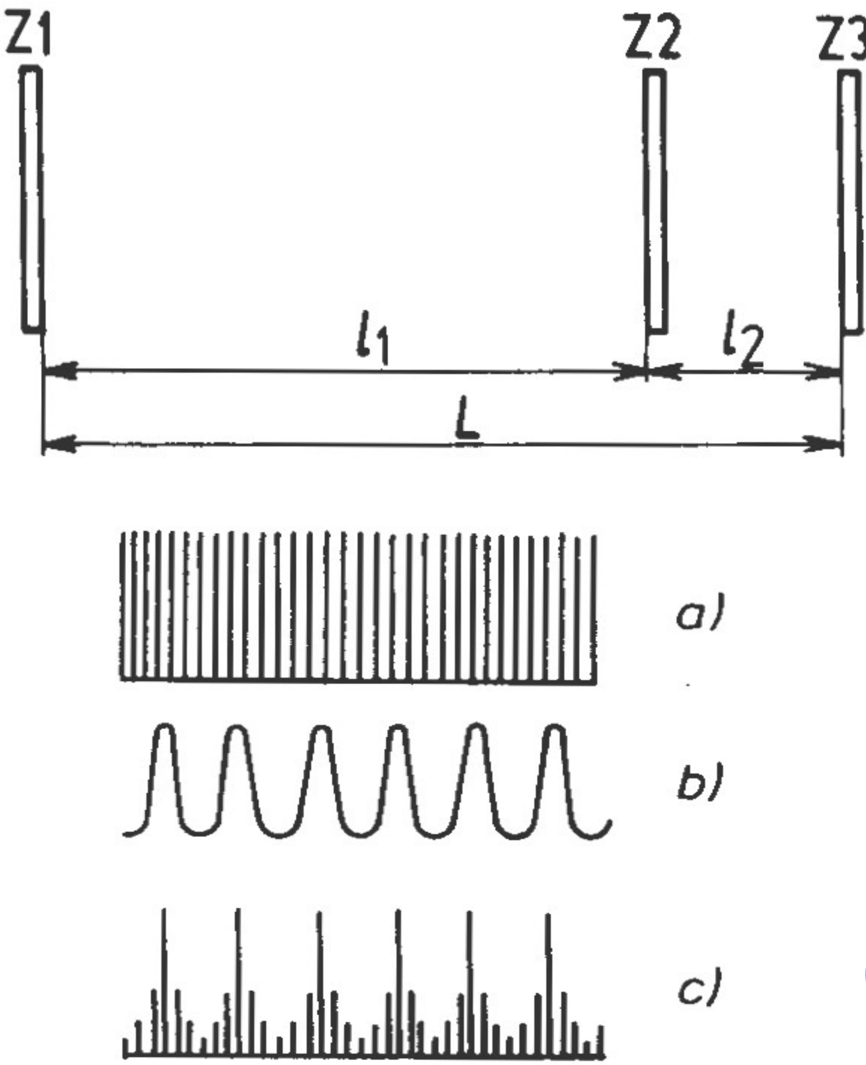
Hemispherical : r1 = L, r2∞

Coupled resonators

L – length of open resonator

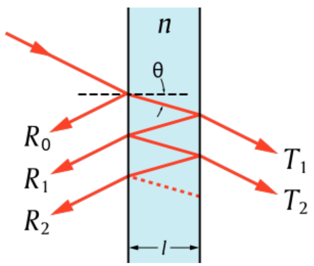
l1,l2 – distance of interior mirrors

a) open resonator modes Z1-Z3
b) internal resonator modes Z2-Z3
c) resulting spectrum of frequencies

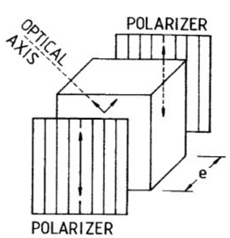


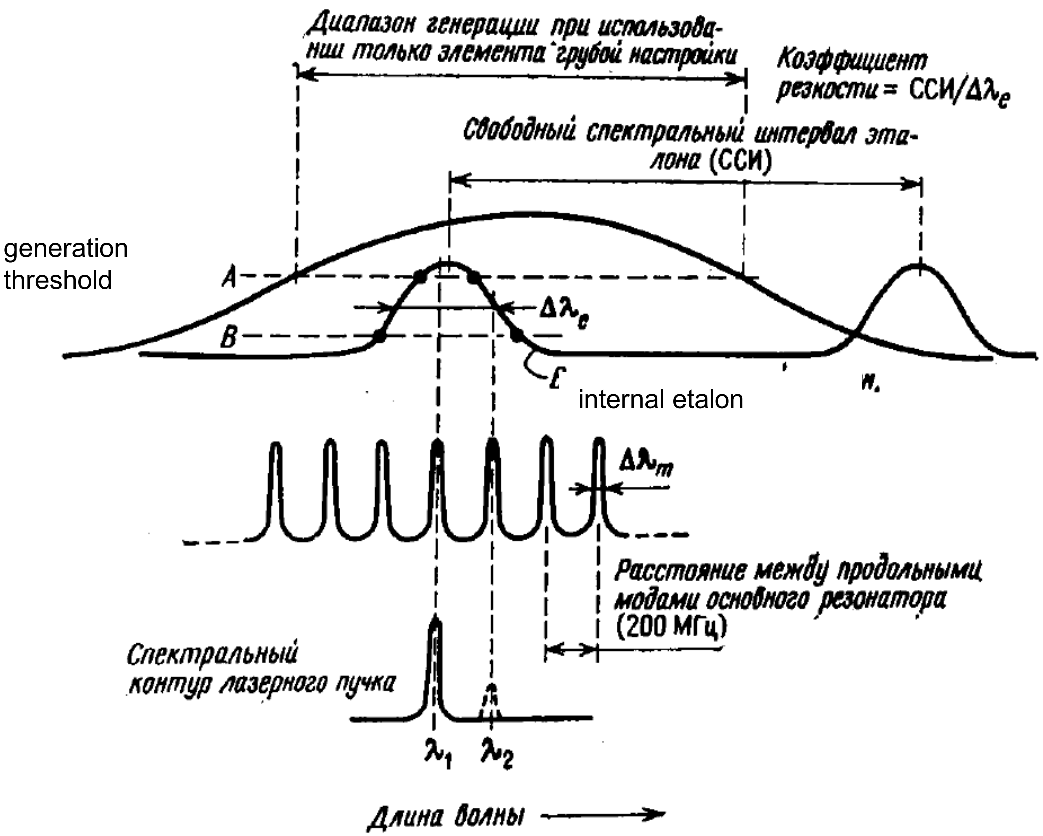
Single mode laser

- Combination of resonant modes and internal FP standard



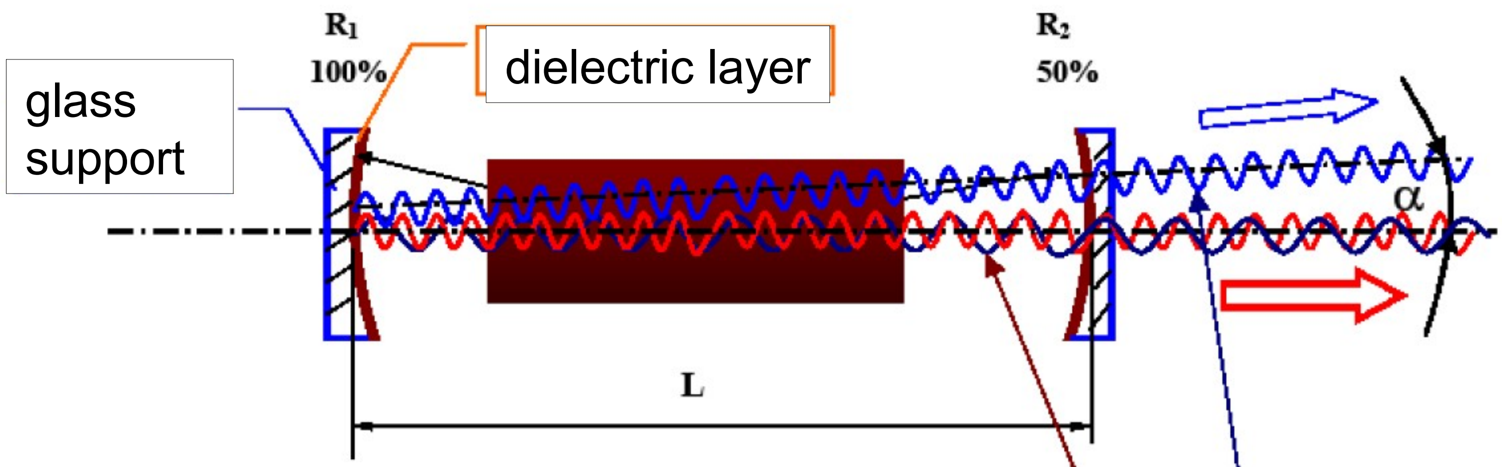
- or Lyot filter (narrowband polarization filter)





and the gain bandwidth generates only one longitudinal mode

Open optical resonator



Open resonator modes :

Longitudinal modes: distribution of light radiation in the longitudinal direction měru

Transverse modes: distribution of light radiation in the transverse direction

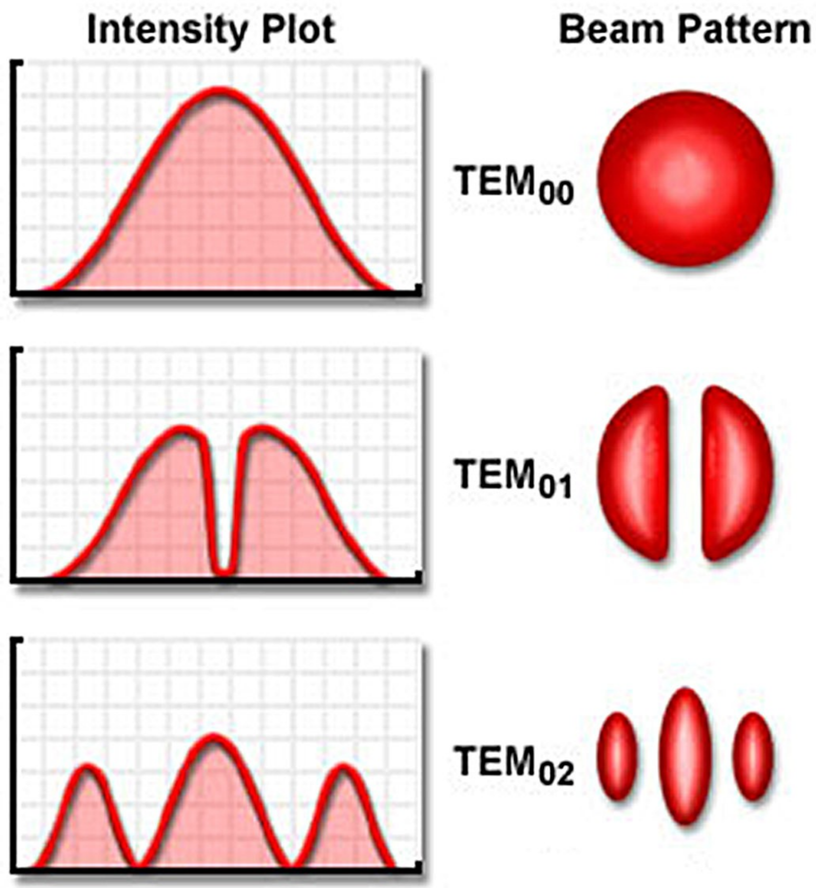
Transverse modes of the resonator

Transverse Electromagnetic Mode - **TEM**

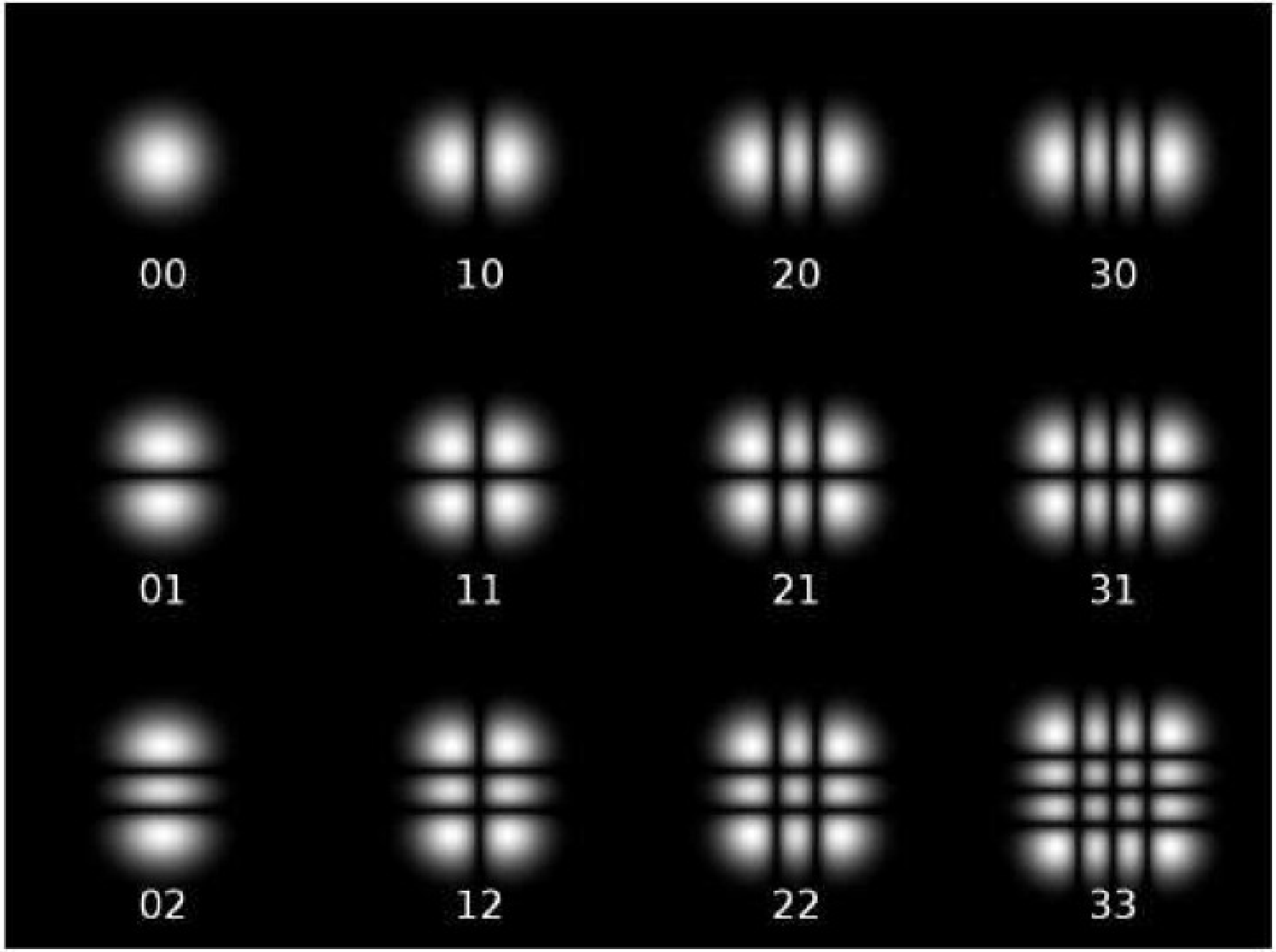
- Transverse modes are characterized by a pair of numbers **m** and **n**. These numbers represent the **number of nodes** of the standing wave on the axes **(x, y)** perpendicular to the optical axis.

- The number of nodes of the standing wave in the optical axis **L** is high and is not given.

- The basic mode is TEM00, in which the radiation intensity profile has a Gaussian profile.



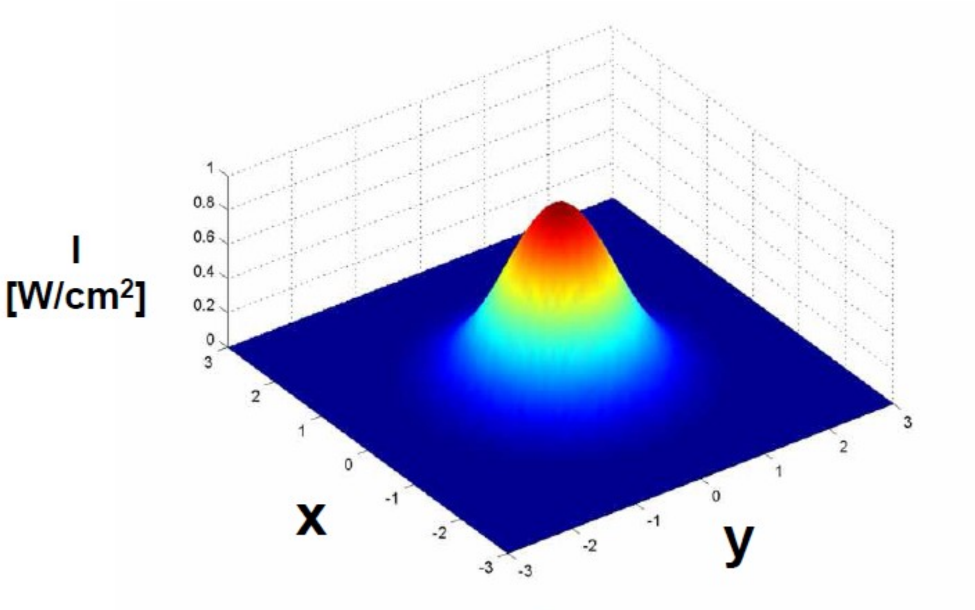
Transverse modes of the resonator



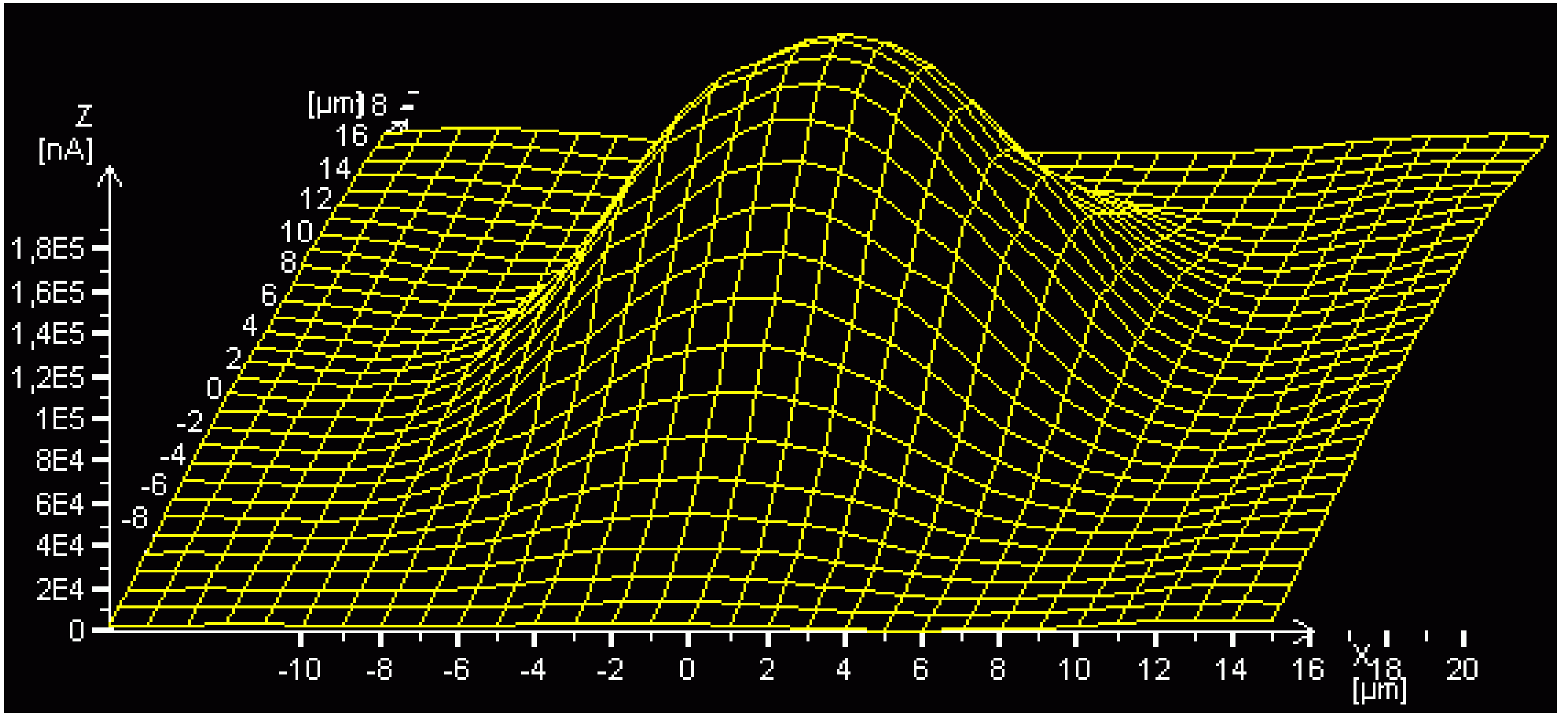
Gaussian beam (profile) mode TEM00

$$f(x) = \exp(-x^2 / w_s^2)$$

ws = distance from the resonator axis, where the radiation intensity decrease to 1/e axis intensity



Profile of the focused laser beam in its focus



Coherence of radiation

coherence length lc- related to how long a continuous electromagnetic wave (sinusoidal wave) is emitted.

$$l_c = c \cdot \tau$$

Heisenberg uncertainty principle : $\delta E \cdot \delta t \approx h / 2\pi$

$h\delta\nu = \delta E \Rightarrow h\delta\nu \cdot \delta t \approx h / 2\pi \Rightarrow \delta\nu \approx 1 / 2\pi\, \delta t$

coherence time– τ

$$\Delta\nu = \frac{1}{\tau}$$

where $\Delta\nu$ is the width of the spectral interval

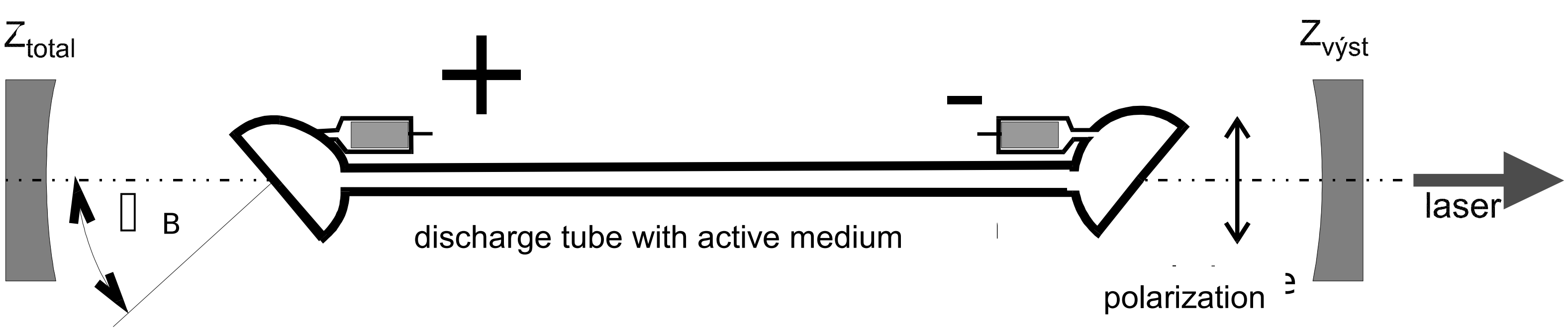
In general, coherence can be understood as the ability of radiation to interfere with relative time shifts of the emitted radiation

Brewster's angle

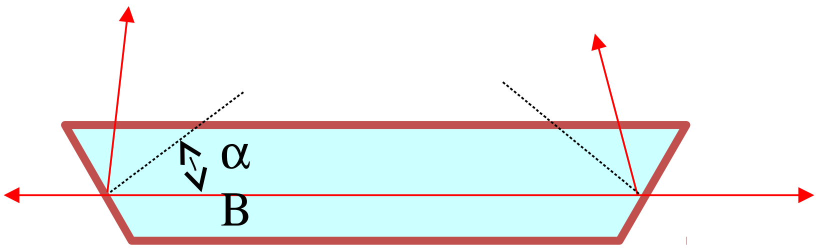
Exit windows separating the low pressure area from the atmosphere they are inclined at **Brewster's angle** to form a lossless optical feedthrough, which, as a by-product, causes the output radiation to be linearly polarized, a feature useful for a variety of applications.
For the size of the Brewster angle, it can be deduced from the Fresnel equations (indicating the intensity of the reflected and refracted light) that:

$$tg(\alpha_B) = n$$

Where αB is the value of the Brewster angle and *n* **relative refractive index between input and output medium.**

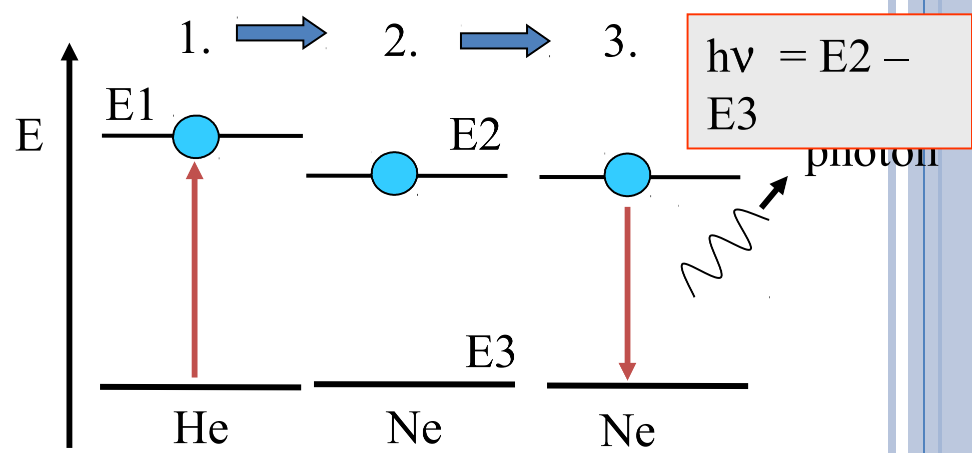


He – Ne and CO2 laser



Energy scheme of excitation
(so-called three-level system)

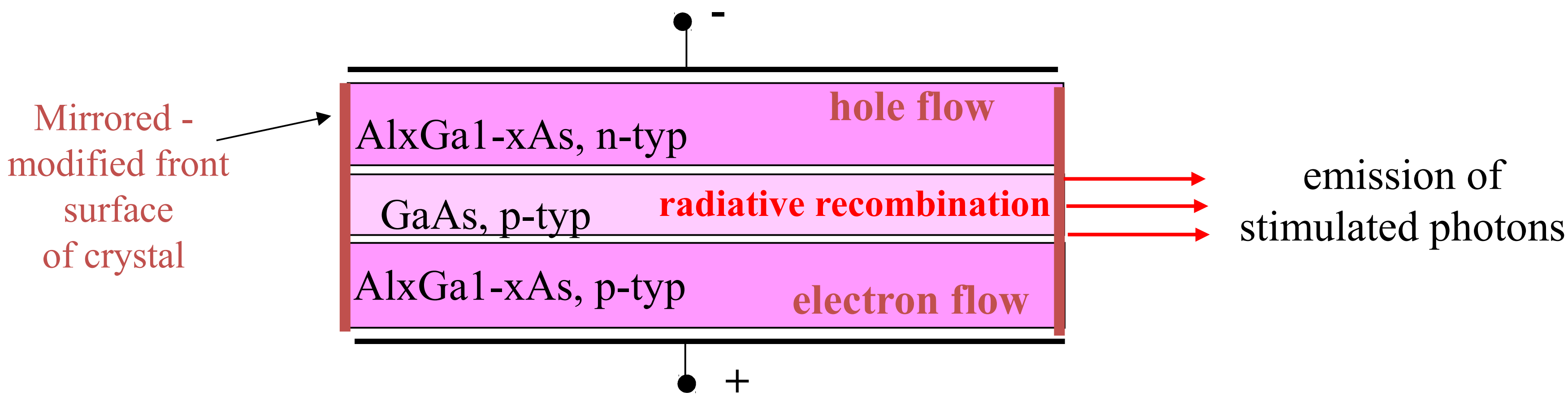
1. If the exit windows are inclined at Brewster angle, the laser beam is linearly polarized
2. Glass discharge tube filled with He (pressure about 100 Pa) and Ne (pressure about 10 Pa).
3. For CO_2 laser: nitrogen takes over the function of He and molecule of CO_2 takes over the function of neon



Typical continuous lasers.
λ(He-Ne) = 632.8 nm
λ(CO_2) = 10.6 μm

1. He atom is excited to E1 by the discharge
2. By collisions He and Ne atoms - Ne atom is excited to a metastable state
3. In the presence of an electric field with a frequency νM the Ne emits stimulated photon, otherwise spontaneous

Semiconductor laser



1. The external voltage of this polarity causes a large **number of electrons and holes** (with a sufficiently long lifetime) to accumulate simultaneously in the optically active layer of **GaA**s, which can only recombine together by **radiative transitions**.
2. The mirrored crystal surface forms a plan-parallel **optical resonator** of about 1 mm in length. This ensures that stimulated photon emission occurs when electrons and holes recombining.Vlnová délka emitovaného světla je z intervalu 700 až 900 nm podle obsahu Al.
3. Luminescent photodiodes (LEDs) work on a similar principle. They do not have a resonator and the electrons and holes in the active environment recombine almost immediately.

Summary

- laser radiation has a much smaller line width than the emission line of the active medium
- the laser emits radiation corresponding to the longitudinal (or transverse) modes, depending on the resonator configuration
- the laser emits only in those modes whose gain is greater than the threshold
- laser radiation has a high coherence
- if the optical system includes an element supporting a particular polarization orientation, the output radiation is polarized.

Literature

- G.M. Hieftje, J.C. Travis, F. E. Lytle. *Lasers in Chemical Analysis,* The HUMANA Press. Inc. 1981
- D. L. Andrews, *Lasers in chemistry,* Springer – Verlag, Third edition, 1997
- N. Omenetto, *Analytical Laser Spectroscopy*, John Wiley & Sons, 18. 1. 1979