"Optical Measurements"

Master Degree in Engineering

Automation-, Electronics-, Physics-, Telecommunication- Engineering

LASER Sources: Principles of Operation

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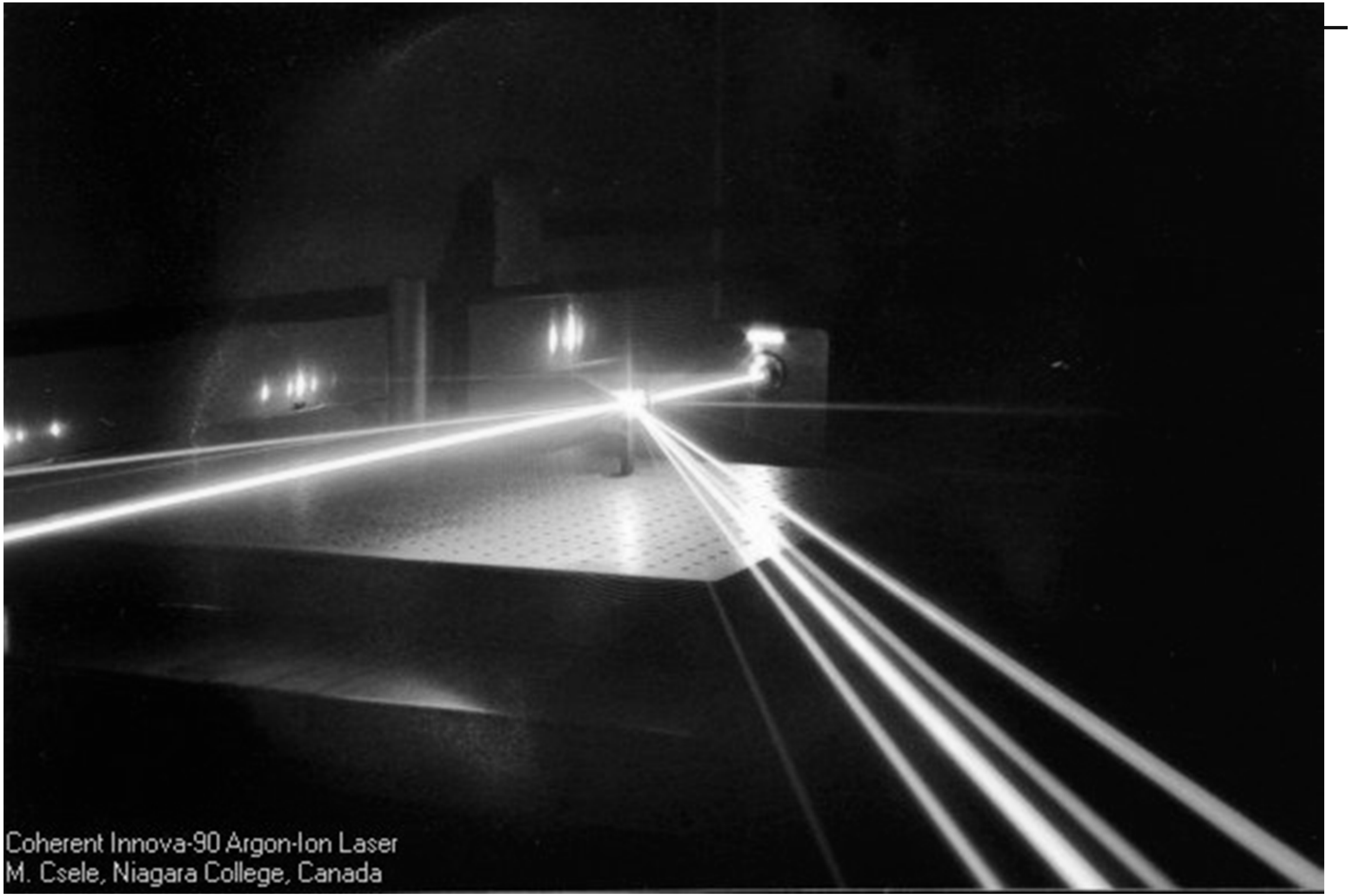
Before it was DARK…

… and now “we have **THE LIGHT**”!



Coherent Innova-90 Argon-Ion Laser
M. Csele, Niagara College, Canada

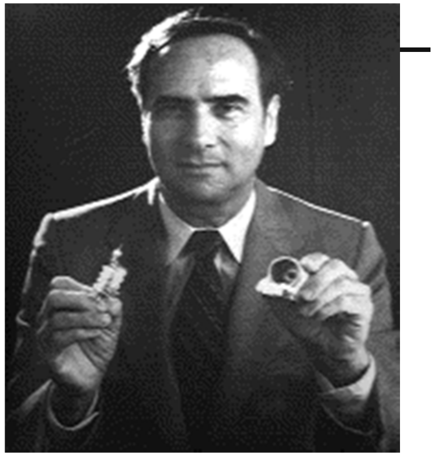
Summary (1)

- Historical perspective, e.m. spectrum, dualism of light
- Stimulated emission, optical amplification, optical resonators, LASER action
- Pump methods and population inversion
- Active media and LASER types
- Gas LASERs (CO_2 and He-Ne)
- Solid-state LASERs with optical pumping (Nd:YAG) [DPSSL]
  - *side-pumped* and *end-pumped* LASERs
- Semiconductor LASERs (Laser Diodes) [LDs]
  - LDs for pointing, optical reading, printers, …
  - Single-Mode LDs for Optical Communications (DFB, DBR, VCSEL)
  - Single-Mode *narrow linewidth* LASERS for precision measurements: Extended-Cavity Laser Diode (ECLD), Er:fiber and Er:bulk LASERs

Summary (2)

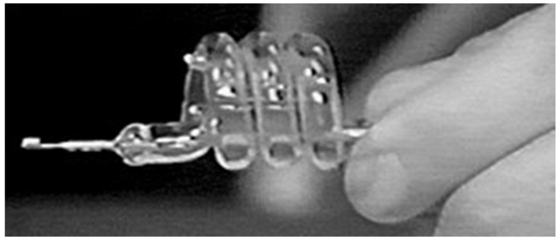
- Pulsed LASERs (*Q-switching* and *mode locking*)
- Examples of prevalent lasers, features, applications
- Propagation and spatial profile measurements
  - *spot size*
  - *divergence*
- Properties of laser beams
  - Spatial and spectral properties
  - Amplitude and frequency noise
- Definition and measurement of optical power
- Direct and coherent optical detection
- Applications of LASERs and laser safety
- Bibliography

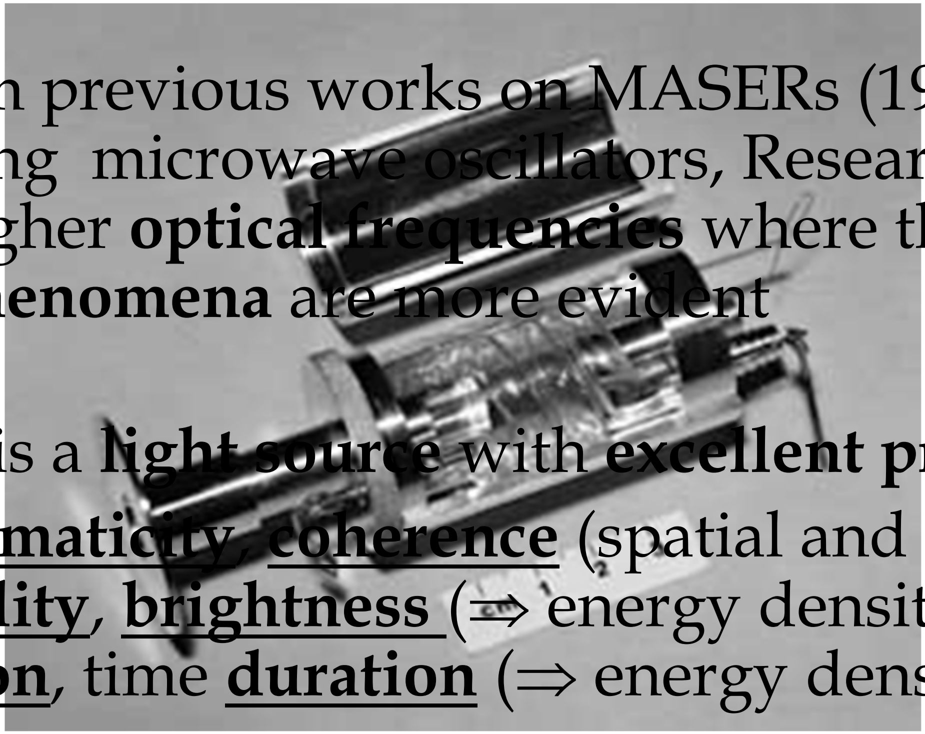
Historical perspective and laser properties



- **LASER** invented in **1960** **(T. Maiman)**

  Light Amplification
  by Stimulated
  Emission of Radiation





- Starting from previous works on MASERs (1954) and the corresponding microwave oscillators, Research moved to the much higher **optical frequencies** where the energetic **quantum phenomena** are more evident

- The LASER is a **light source** with **excellent properties**:

  monochromaticity, **coherence** (spatial and temporal),
  directionality, **brightness** (⇒ energy density in space),
  polarization, time **duration** (⇒ energy density in time)

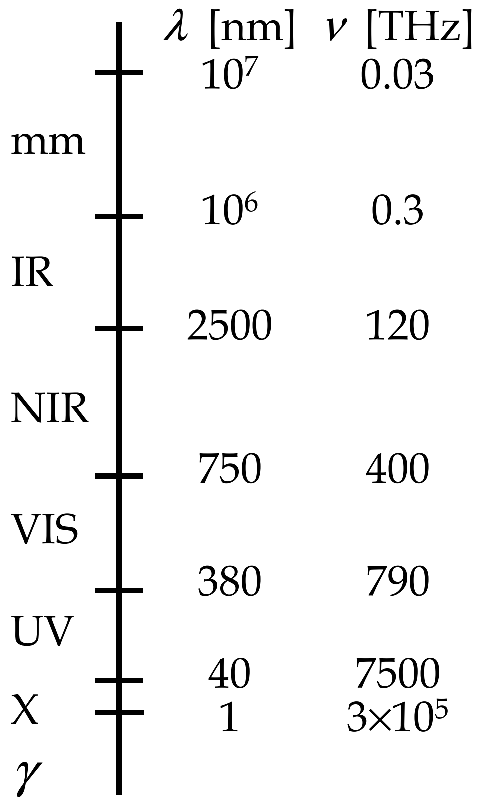
The electro-magnetic spectrum

- **Oscillators** at **“optical” frequencies** ($f \sim 500$ THz)

  $f \rightarrow \nu$ with $\lambda = c/\nu$ **wavelength**

color λ (nm)
red 750-620
orange 620-585
yellow 585-575
green 575-500
blue 500-445
indigo 445-425
violet 425-380

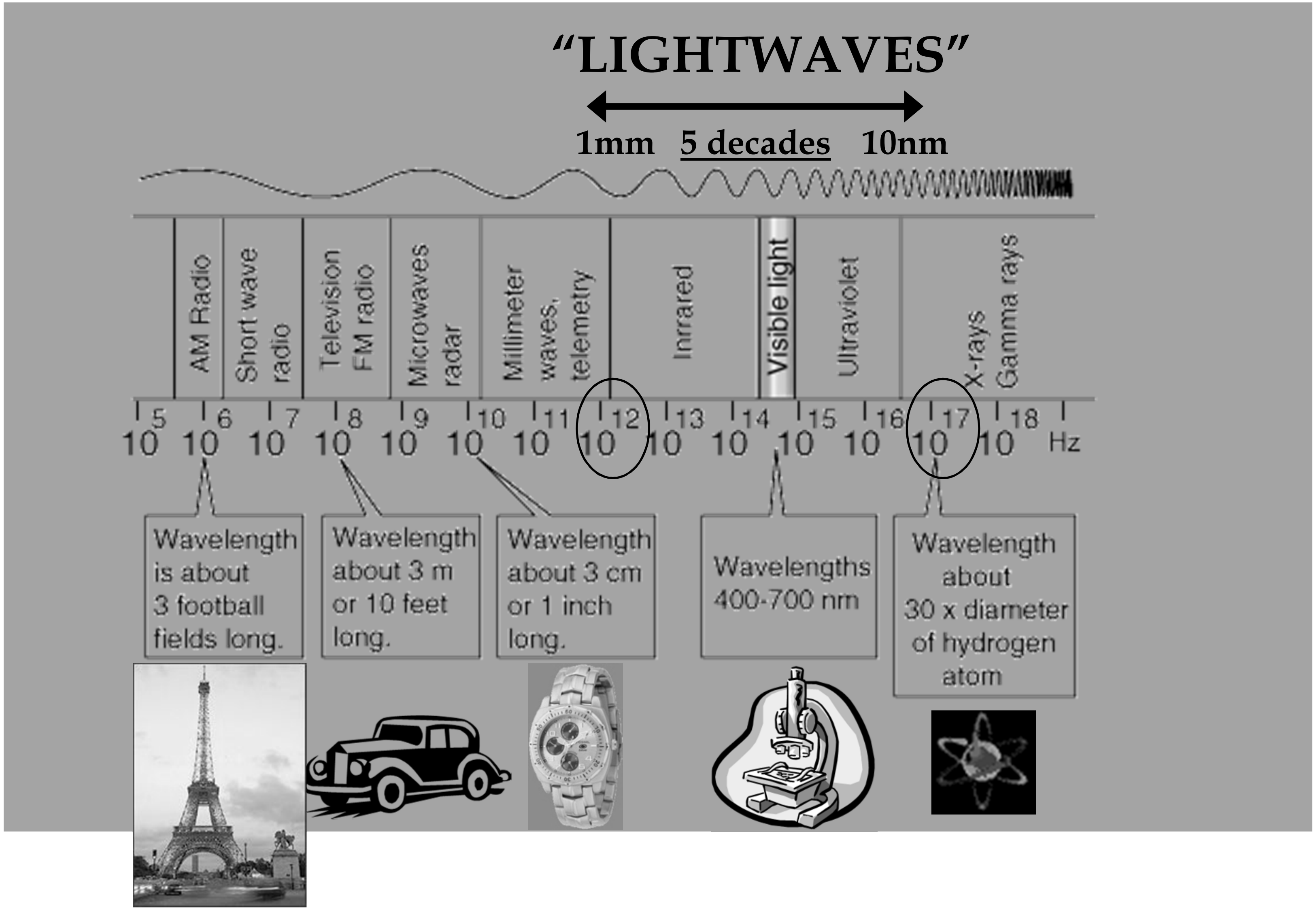
  - millimeter waves (10mm-1mm)
  - Far- and Medium- IR (1000μm -2.5μm)
  - Near-IR (2.5-0.75μm)
  - **VISible (750nm-380nm)**
  - UV (380nm-40nm)
  - X-rays *soft* (40nm-1nm)
  - X-rays *hard* (1nm-0.01nm)
  - γ rays(10pm-0.01pm)



- LASERs working in **CW or PULSED regime**

  (optical carrier stationary or modulated)

“Optical” wavelengths (LightWaves)

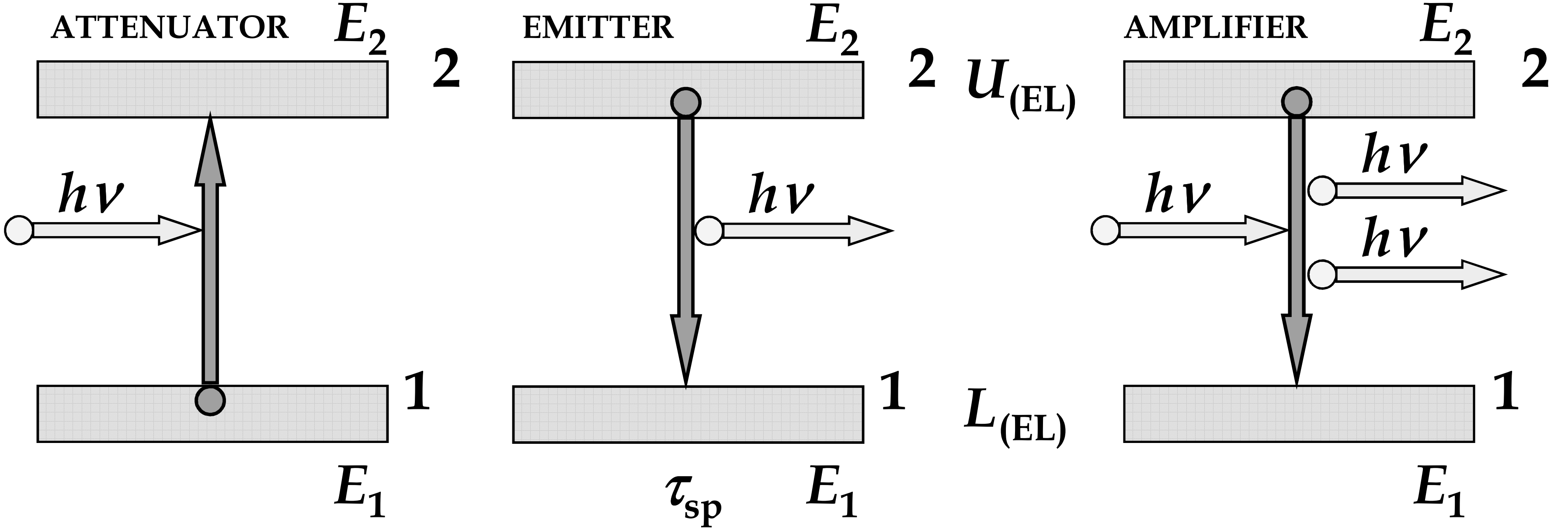


Representations of light

- **WAVE** (wave theory)
  - interference phenomena
  - diffraction phenomena
- **PHOTON** (corpuscle theory)
  - energy quantization $E=h\nu$
  - interaction radiation/matter (photon absorption/emission)
- **RAYS** (geometrical optics)
  - analysis of optical systems: reflection/refraction
  - most finely: Gaussian Optics

Absorption, spontaneous emission, stimulated emission

((*all effects are due to different energy states in the atom*))



absorption **spontaneous emission** **stimulated emission**

$h\nu = E_2 - E_1$

$\lambda = hc/(E_2 - E_1)$

In the process of **stimulated emission**, an incident **photon** is **"amplified"** producing **two coherent photons** (***interaction of light with excited atoms***)

Optical amplification (coherent)

Spontaneous Emission: (*incoherent emission*)

energy is emitted with frequency not exactly predetermined and with random phase and direction

Stimulated Emission: (*coherent emission*)

energy is emitted with the same frequency, phase, direction

ENERGY LEVELS

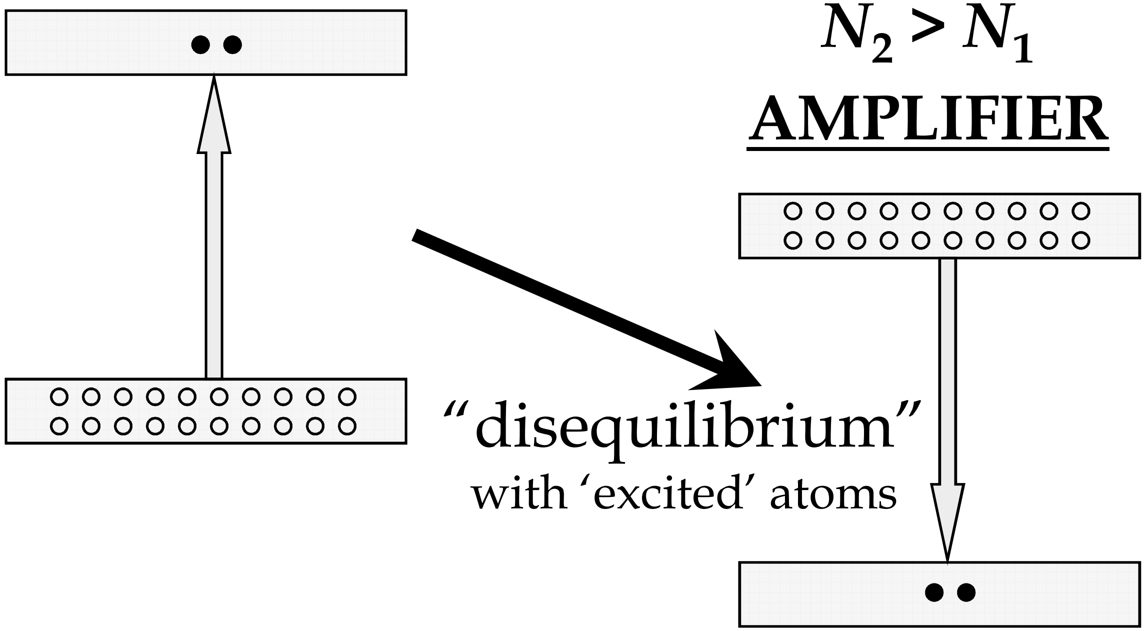
upper: E_2
lower: E_1

- **atoms**
- **ions in glass or crystal**
- **molecules (*also vibrational*)**
- **bands (semiconductors)**

Population inversion

At thermodynamic equilibrium,
with $E_2 > E_1$,
it is $N_2 < N_1$

$N = [1/\text{cm}^3] =$
$= [\text{atoms/cm}^3]$



$N_2 < N_1$
ATTENUATOR

$N_2 > N_1$
AMPLIFIER

"disequilibrium"
with 'excited' atoms

$\underline{\Delta N = (N_2 - N_1)}$ <u>is called POPULATION INVERSION</u>

If $N_2 = N_1$ (which holds also for $N_2 = N_1 = 0$) the medium is "**transparent**" to the specific ν and λ considered

Elements of a LASER oscillator

1. **Active MEDIUM**
atoms/ions/molecules with “suitable” **energy levels**

2. **PUMP** mechanism
energy transfer to provide for **“population inversion”**, by “exciting” the active medium and obtain **optical gain**

3. **Optical RESONATOR**
system for **e.m. radiation confinement**

1. + 2. → device with GAIN
amplifier (*LASER action*)

3. → way for optical feedback
feedback (+)

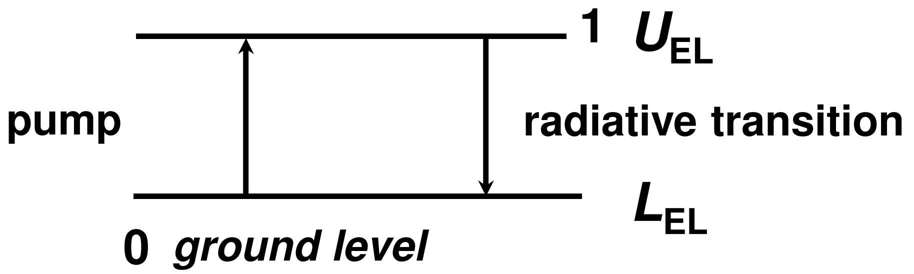
⇒ **OSCILLATOR**
(*laser oscillation*)

Optical amplification (??? 2 levels)

Even by supplying energy to the system, it is impossible to achieve ("net") amplification by a system with 2 energy levels

When $N_1=N_0=N/2$ any additional pump energy gives the same probability of transition 0→1 and 1→0

Two-level system



condition for amplification: $N_1 > N_0$ (impossible)

"It is not sufficient to promote $N/2$ atoms in the upper level"
(and it is not possible promoting more than $N/2$)

Optical amplification (3 levels)

In order to obtain amplification we must supply energy to a system with more than 2 levels

⬇

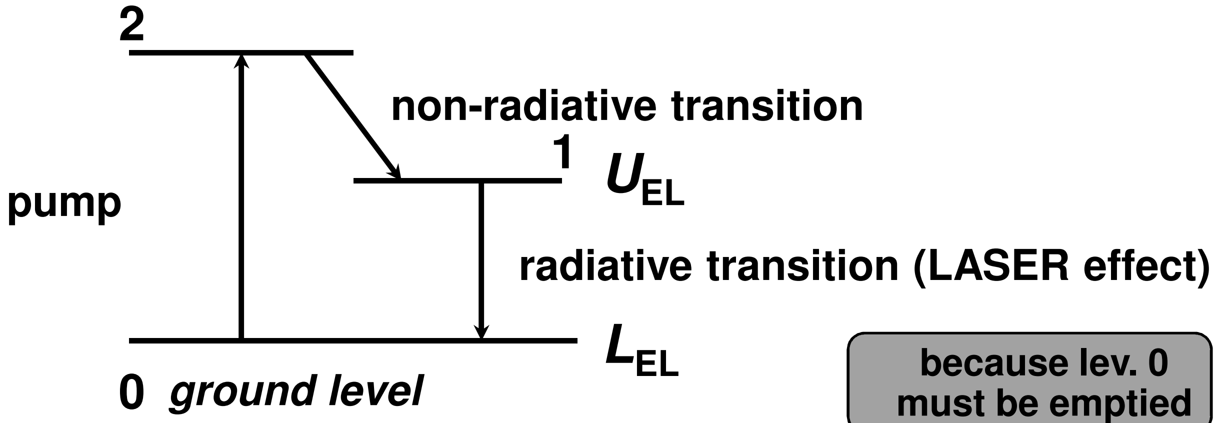
POPULATION INVERSION

$N_1 - N_0 > 0$

Three-level system

working condition

$\tau_{21} << \tau_{10}$



2

non-radiative transition

1 U_{EL}

pump

radiative transition (LASER effect)

L_{EL}

0 *ground level*

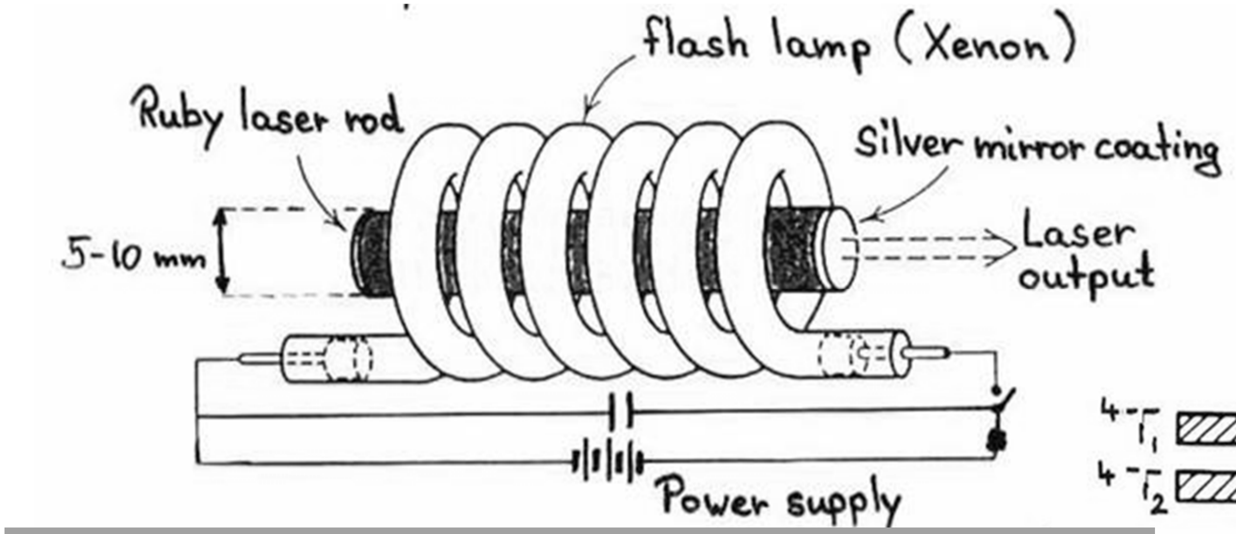
because lev. 0 must be emptied

condition for amplification: $N_1 > N_0$ (not simple)

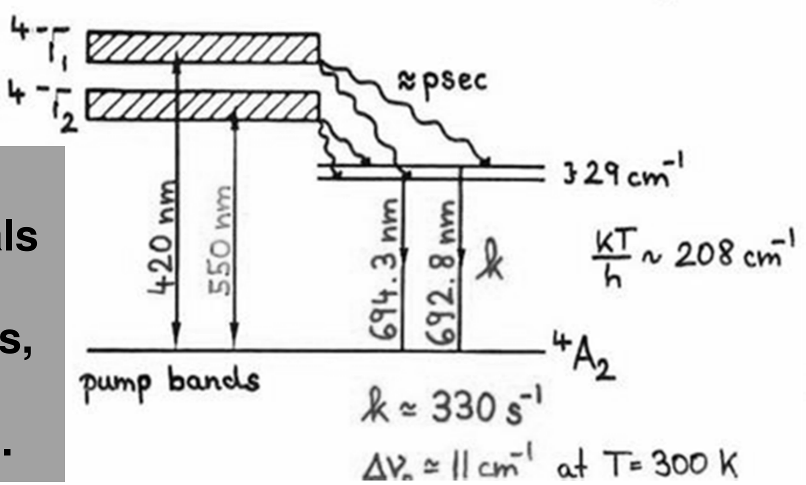
"We must promote $N/2+n$ atoms in the upper level"

Example of 3-level LASER (Ruby)

Ruby: **Al_2O_3 (aluminum oxide: α-alumina, or corundum) where some of the Al^{3+} ions are substituted by Cr^{3+}**



Cr_2O_3 (by-weight) substitution for Al_2O_3 in Natural Ruby is ≈1%
Synthetic Ruby is 0.05%



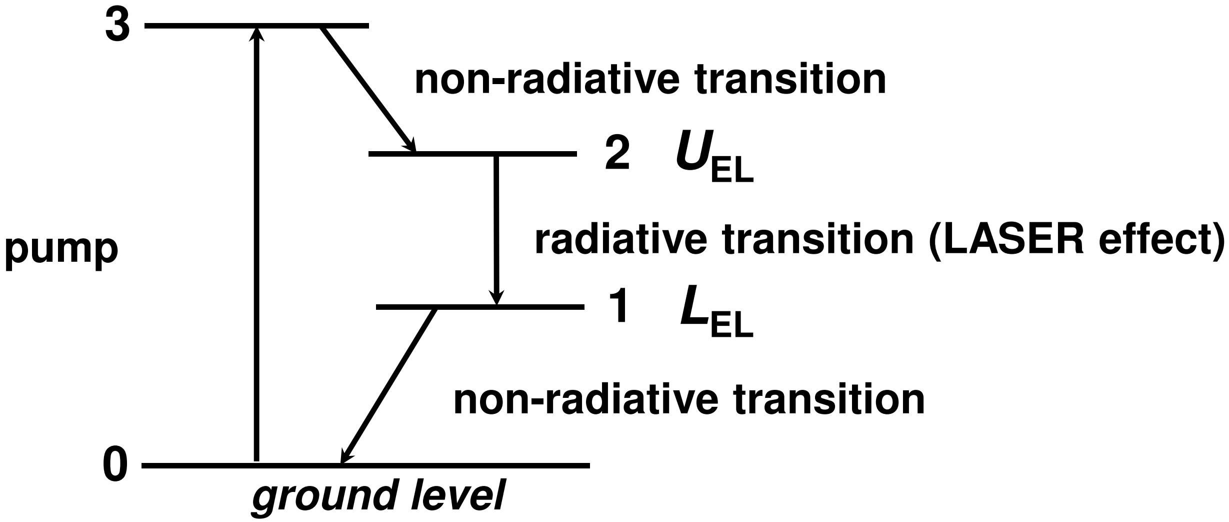
IN GENERAL:
The procedure of doping tiny amounts of the metals chromium (Cr), neodymium (Nd), erbium (Er), thulium (Tm), ytterbium (Yb), and a very few others, into transparent crystals, ceramics, or glasses provides the active medium for solid-state lasers.

$$\lambda_{P,\text{visible(BLUE-GREEN)}} = 0.42\text{-}0.55\ \mu m < \lambda_L = 0.69\ \mu m$$

Optical amplification (4 levels)

Most efficient system: 4 LEVELS

Four-level system



3

pump

non-radiative transition

2 U_{EL}

radiative transition (LASER effect)

1 L_{EL}

non-radiative transition

0

ground level

working condition

$\tau_{32}\ ,\ \tau_{10} << \tau_{21}$

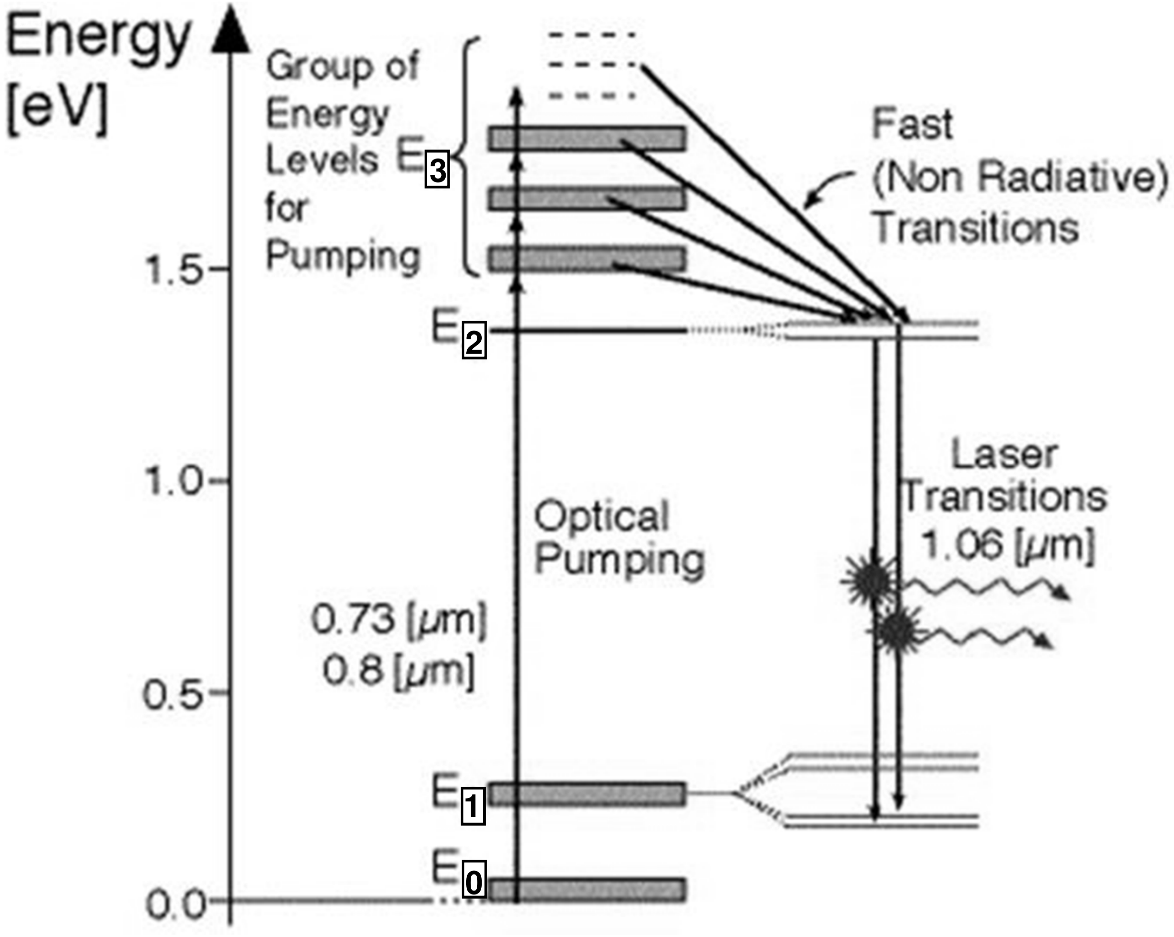
because lev. 1 is already empty

condition for amplification: $N_2 > 0$ (simple)

"It is sufficient to promote **any *n*** atoms in the upper level"

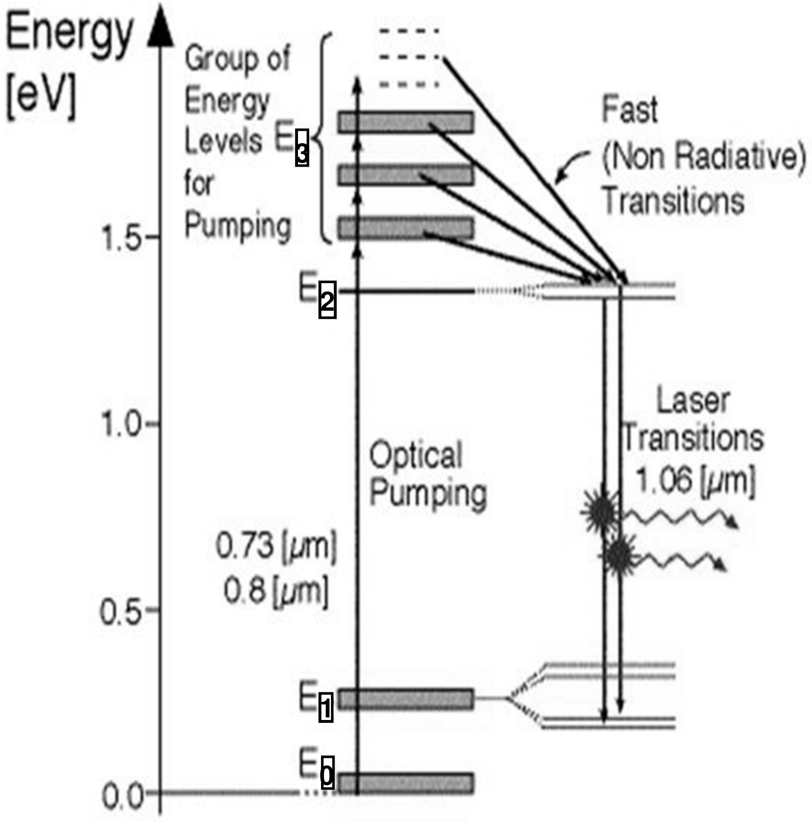
Example of a 4-level LASER (Nd:YAG)

YAG: Yttrium Aluminum Garnet ($Y_2Al_5O_{12}$)
with some Y^{3+} atoms/ions substituted by Nd^{3+} (≈1%)



Nd:YAG LASER and *"Quantum defect"*

Energy E_P of the pump photon must be higher than energy E_L of laser photon ($\boldsymbol{h\nu_P > h\nu_L}$)



$\boldsymbol{\lambda_P = 0.8\ \mu m < \lambda_L = 1.06\ \mu m}$

$E_P = h\nu_P = hc/\lambda_P \cong 2.46\times10^{-19}$ J

$E_L = h\nu_L = hc/\lambda_L \cong 1.87\times10^{-19}$ J

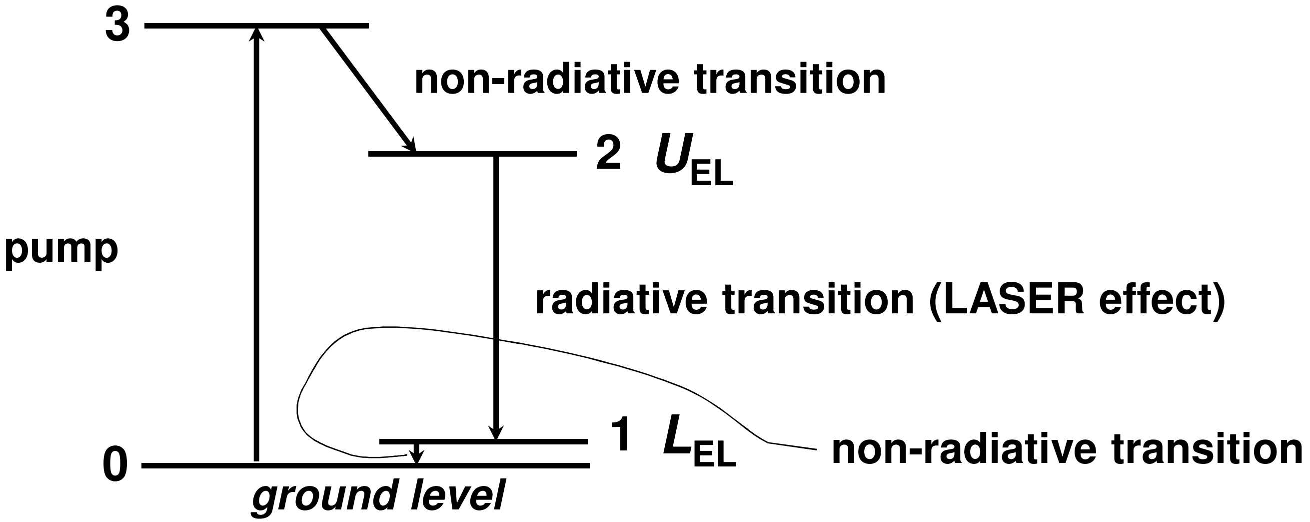
$\underline{\Delta E} = 5{,}92\times10^{-20}$ J $\boldsymbol{\Delta E / E_P = 24\ \%}$

this energy gets "lost" and is provided to the atoms of the crystal in the form of reticle vibrations (phononic excitation) turning into **temperature rise** of the active medium

Optical amplification (quasi-3-levels)

Intermediate behavior: 4-3 LEVELS

Quasi-3-level system



working condition

τ_{32} , $\tau_{10} \ll \tau_{21}$

because lev. 1 is partly (*m*) full

condition for amplification: $N_2 > 0$ (not so simple)

"We must promote ***n* > *m*** atoms in the upper level"

Yb:YAG LASER, low *Quantum defect*

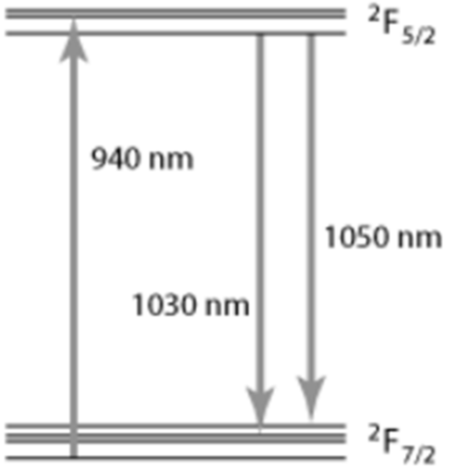


Figure 1: Energy levels of Yb^{3+} ions in Yb:YAG, and the usual pump and laser transitions.

Energy E_P of pump photon must be higher than energy E_L of laser photon ($h\nu_P > h\nu_L$)

$$\lambda_P = 0.94\ \mu m \ < \ \lambda_L = 1.03\ \mu m$$

$$E_P = h\nu_P = hc/\lambda_P \cong 2.12\times10^{-19}\ J$$

$$E_L = h\nu_L = hc/\lambda_L \cong 1.93\times10^{-19}\ J$$

$\underline{\Delta E}$ = 1,85×10^{-20} J **$\Delta E / E_P$ = 8.7 %**

<u>this energy gets “lost”</u> and is provided to the atoms of the crystal in the form of reticle vibrations (phononic excitation) turning into **temperature rise** of the active medium

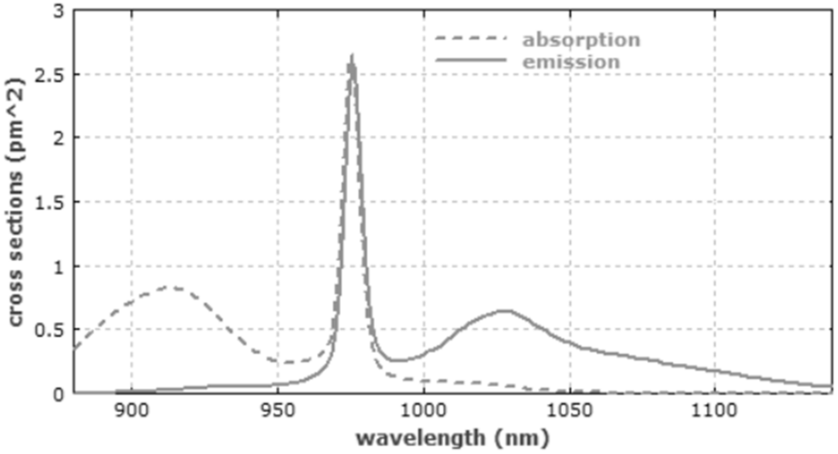


Figure 2: Absorption and emission cross sections of ytterbium-doped germanosilicate glass, as used in the cores of ytterbium-doped fibers.

Er:glass LASER “*quasi-three-level*”

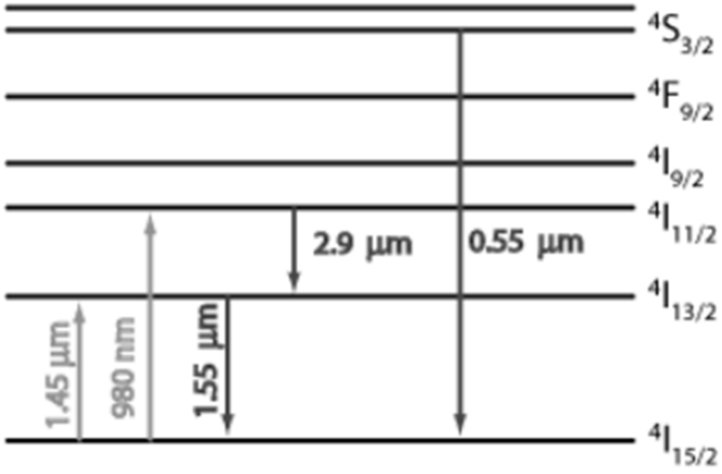


Figure 1: Energy level structure of the trivalent erbium ion, and some common optical transitions.

λ_P= 0.98 µm < λ_L = 1.55 µm

Optical gain and emitted **wavelengths** **<u>from 1480 nm to 1620 nm</u>**: 3th transmission window of optical fibers (loss <0.2dB/km). A complicated balancing mechanism between gain and losses (depending also on the pump rate) allows **broad wavelength emission spectrum**

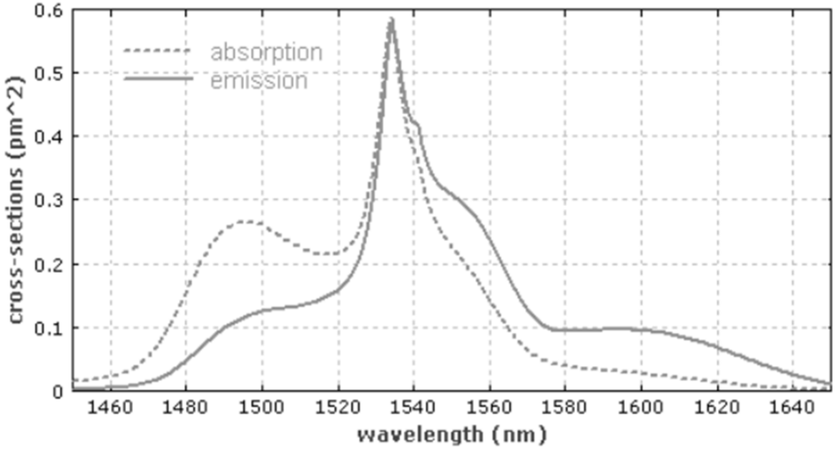


Figure 2: Absorption and emission cross sections for erbium ions in Er:Yb-doped phosphate glass

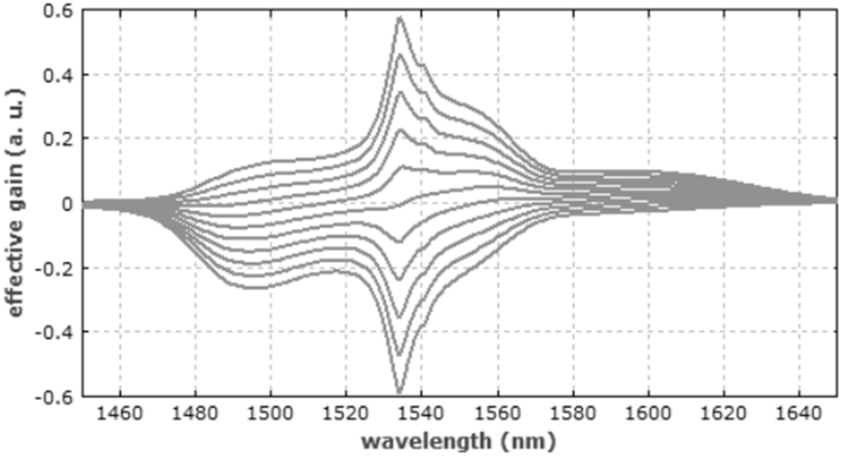


Figure 3: Effective gain from the data in Figure 1, with a degree of excitation from 0 to 100% in steps of 10%.

Summary of “LASER level” schemes

3-level **4-level** **quasi-three-level**

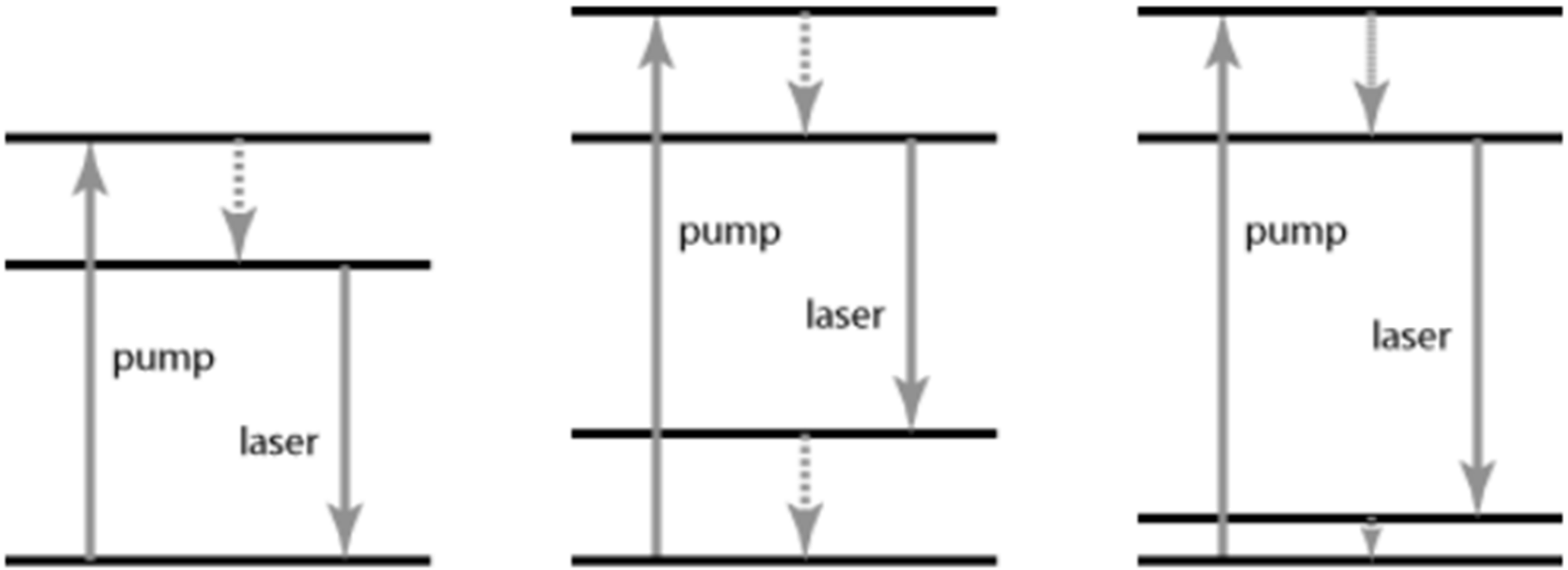
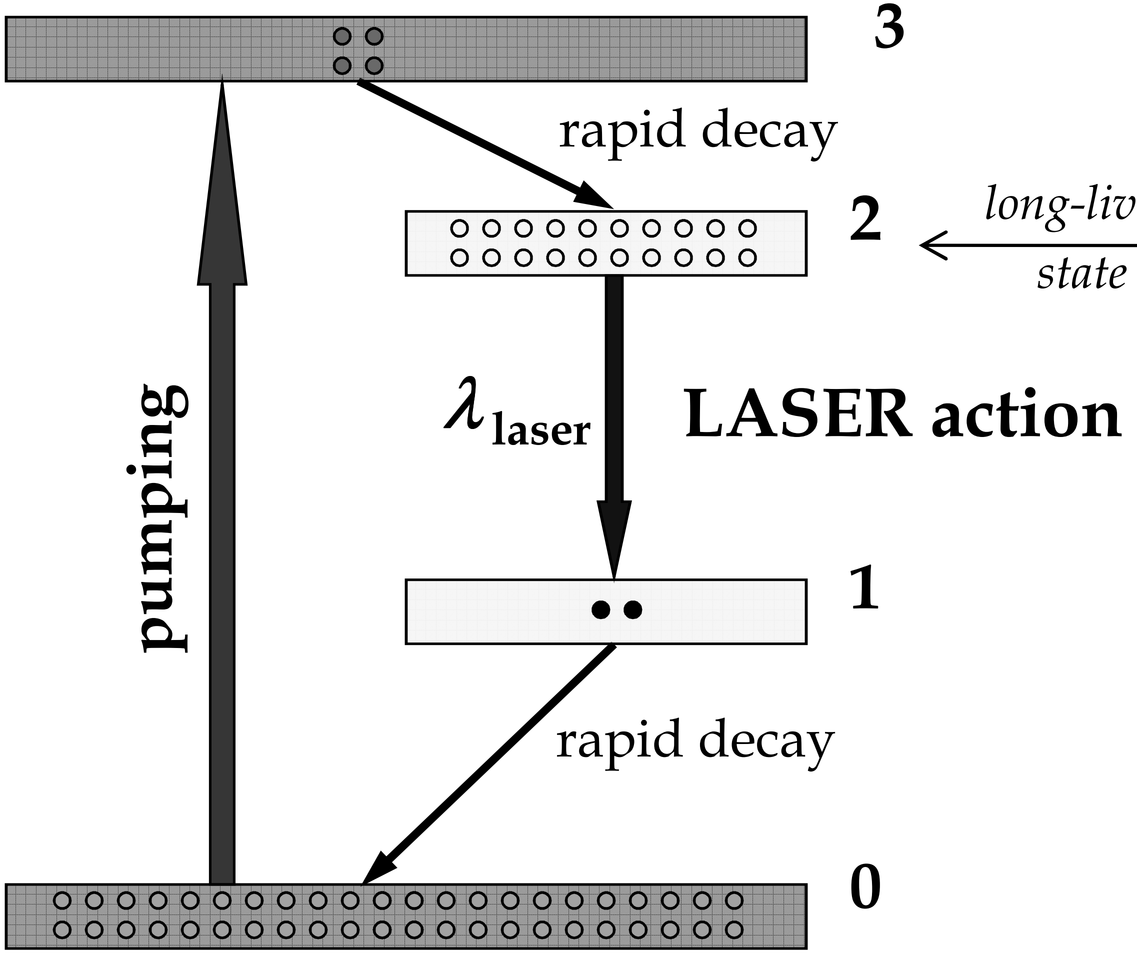


Figure 1: Energy level diagrams of different laser systems. The horizontal lines indicate energy levels; the high a line, the higher the corresponding energy. Left: a three-level system, where the laser transitions ends on the ground state. Middle: a four-level system, where the laser transition ends on a level above the ground state, which is quickly depopulated e.g. via phonons. Right: a quasi-three-level system, where the lower laser level has some population in thermal equilibrium.

Types of pumping mechanisms

- **ELECTRICAL DISCHARGE** (gases)
  - the energy of the electrical discharge excites, via collisions (kinetic energy transfer) the atoms/ions in the active medium
- **OPTICAL** (crystals, gases, liquids)
  - the pump photons excite atoms/ions
- **ELECTRICAL CURRENT** (semiconductor)
  - the energy of the electrical current in the semiconductor (energy of electron-hole recombination) provides emitted radiation

Review of energy levels, pumping, and population inversion (4 lev.)



$N_3 \cong 0 \cong N_1$

$\tau_{21} >> \tau_{32}, \tau_{10}$

Population inversion:

$\mathbf{N_2 > N_1 \cong 0}$

The active medium can **amplify** radiation at λ_{laser}

Optical gain in an active medium

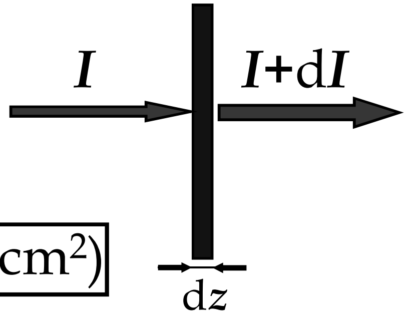
Amplification by unit of length (dz) in the active medium

emission *cross section* (cm^2 or pm^2)

$$\frac{\mathrm{d}I}{\mathrm{d}z} = \sigma \underbrace{\left(N_2 - N_1\right)} I$$

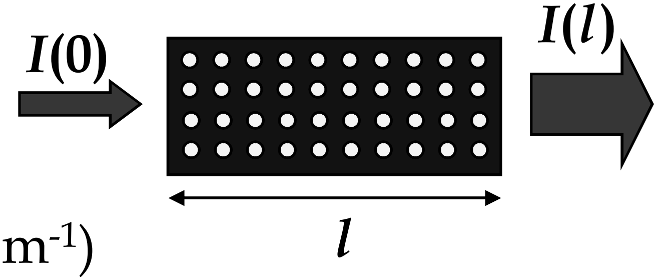
optical intensity (W/cm^2)

ΔN population inversion (cm^{-3})



For an active medium of length l:

$$I(l) = I(0)\exp\left[\underbrace{\sigma\left(N_2 - N_1\right)}_{\text{logarithmic gain } g\ (\text{cm}^{-1})} l\right]$$



$$\frac{I(l)}{I(0)} = G = \exp\left[g\,l\right]$$ **<u>single-pass</u> optical gain**

Elements of a LASER oscillator (*bis*)

1. **Active MEDIUM**
atoms/ions/molecules with "suitable" **energy levels**

2. **PUMP** mechanism
energy transfer to provide for **"population inversion"**, by "exciting" the active medium and obtain **optical gain**

SEEN

3. **Optical RESONATOR**
system for **e.m. radiation confinement**

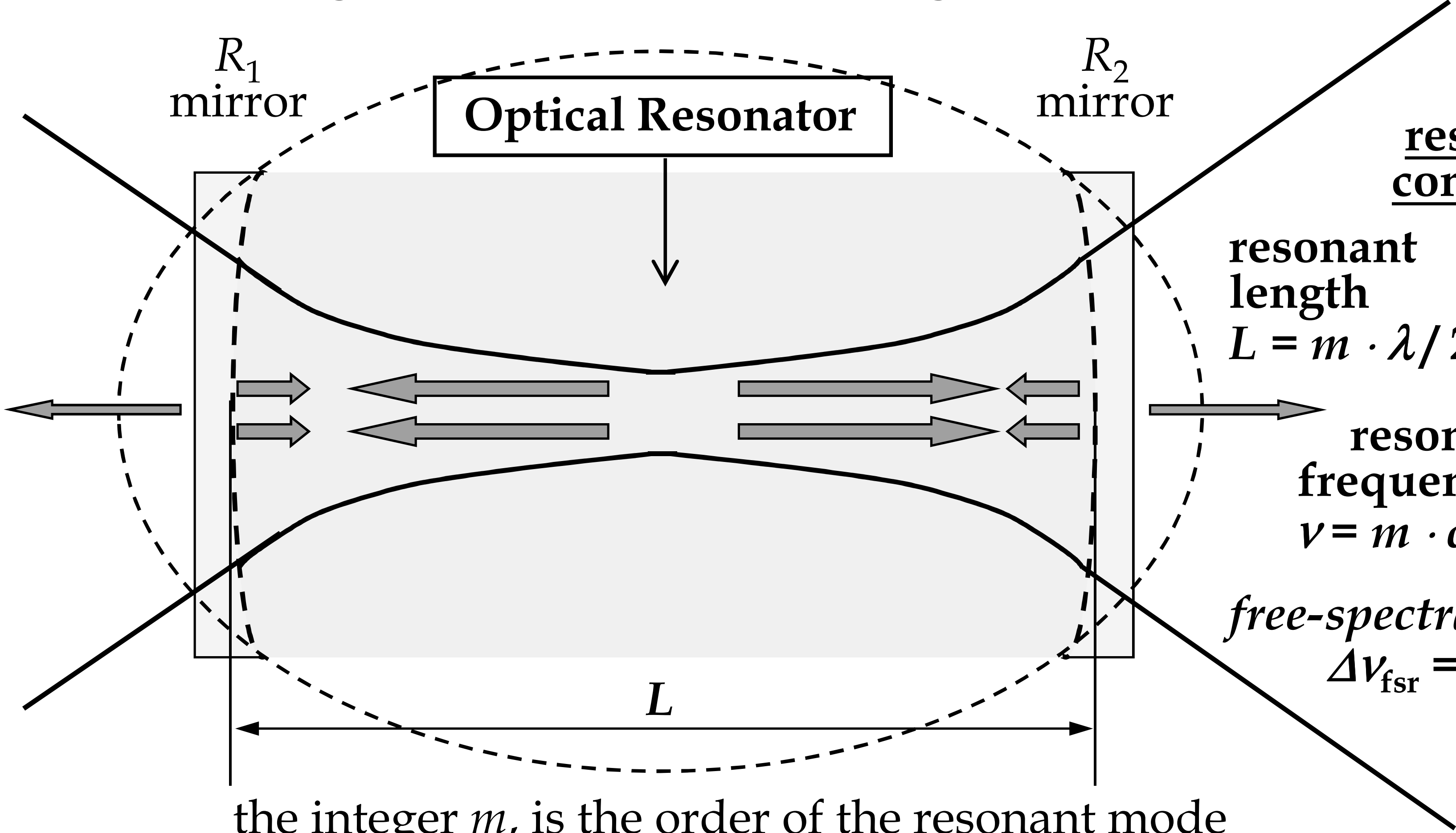
1. + 2. → device with GAIN
amplifier (*LASER action*)

3. → way for optical feedback
feedback (+)

⇒ **OSCILLATORE**
(*laser oscillation*)

Fabry–Perot optical resonators

In order to maintain the **same phase of the e.m. field** for the wave traveling back and forth between the mirrors, the **round-trip path** must be an **integer multiple of the wavelength**: $\underline{2L = m \cdot \lambda}$



resonance conditions

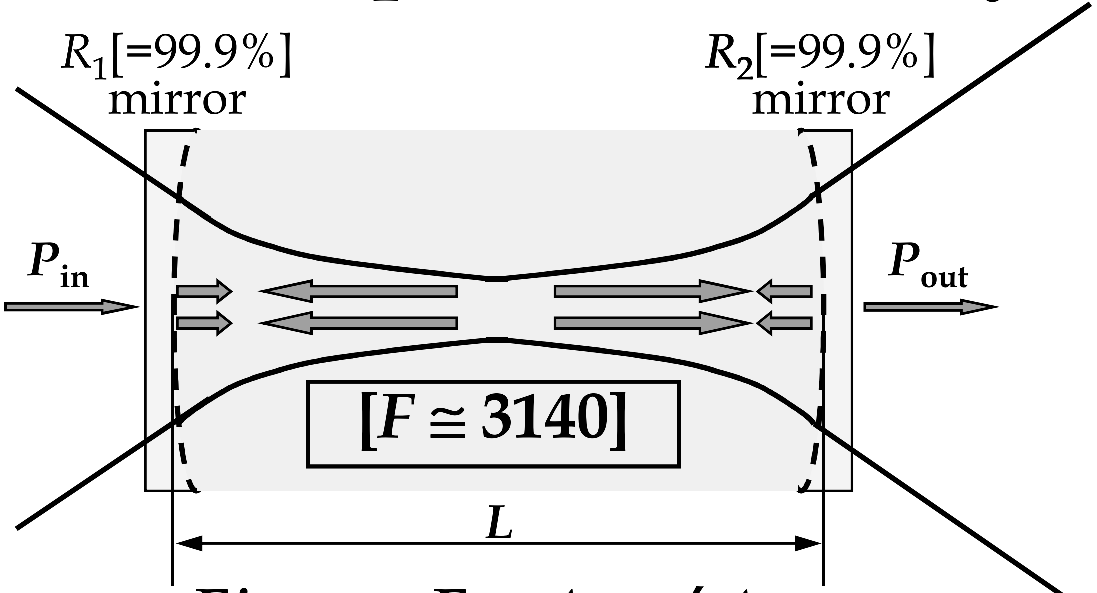
resonant length
$L = m \cdot \lambda / 2$

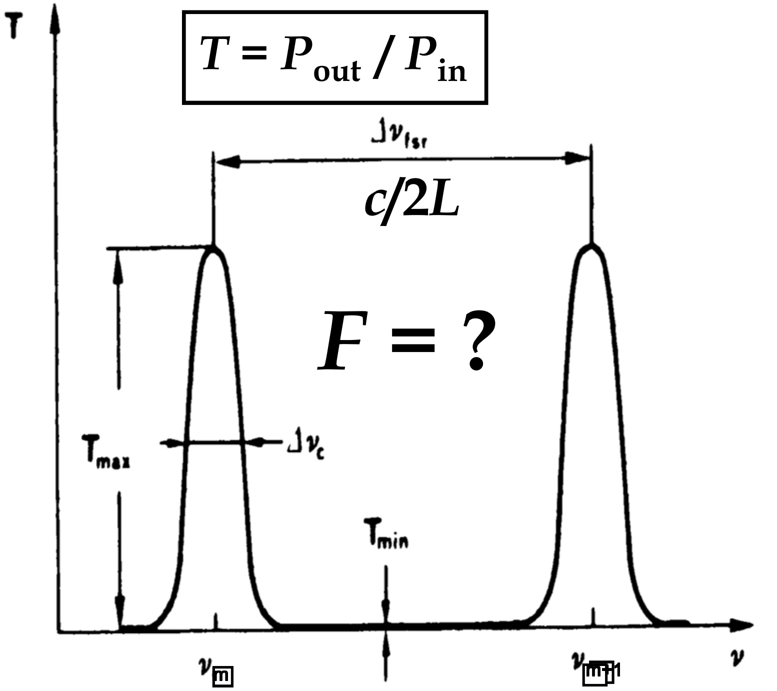
resonant frequencies
$\nu = m \cdot c / 2L$

free-spectral range
$\Delta\nu_{\text{fsr}} = c / 2L$

the integer *m*, is the order of the resonant mode and tells us how many λ are in a *round-trip* (2*L*) or on which order of the FSR is the frequency ν

Properties of Fabry-Perot resonator





Finesse $F = \Delta\nu_{fsr} / \Delta\nu_c$

$F = \pi(R_1R_2)^{1/4} / \{1-(R_1R_2)^{1/2}\}$

$\boxed{F = \pi R^{1/2}/(1-R)}$ **with** $R=R_1=R_2$

("best mirrors" provided F=600 000, hence R=99.9995%=1-T-A "indirect meas.")

$$\gamma = \frac{1}{\pi}\frac{(\Delta\nu_c)}{(c/2L)} = \frac{1}{\pi}\frac{1}{F}$$

$$\gamma = \frac{(L/c)}{(\tau_c)}$$

constant γF ; $\gamma\tau_c$

Cavity linewidth

$\Delta\nu_c = 1/2\pi\tau_c = c\gamma/2\pi L$

Cavity lifetime

$\tau_c = L/c\gamma$

γ losses (logarithmic) per pass (see later)

Quality factor

$Q = (\nu/\Delta\nu_c)^{-1} = \nu/\Delta\nu_c$

$Q = (\nu/\Delta\nu_{fsr})\cdot F$

$Q = m \cdot F$

Transmission of the Fabry-Perot

Airy spectral profile

$$T(\varphi)=\frac{(1-R)^2}{1+R^2-2R\cos\varphi}$$

$\cos(\varphi)=+1 \Rightarrow \varphi = n(2\pi)$

$\cos(\varphi)=-1 \Rightarrow \varphi = n(2\pi)+\pi$

for $R=R_1=R_2$

round trip

$$\varphi = (2\pi\cdot 2L/\lambda) = (ks) = (2\pi\cdot \nu \cdot 2L/c)$$

$$\frac{\nu}{\Delta\nu_{\text{fsr}}}$$

Linear axis
in φ or ν
(**not** in λ)

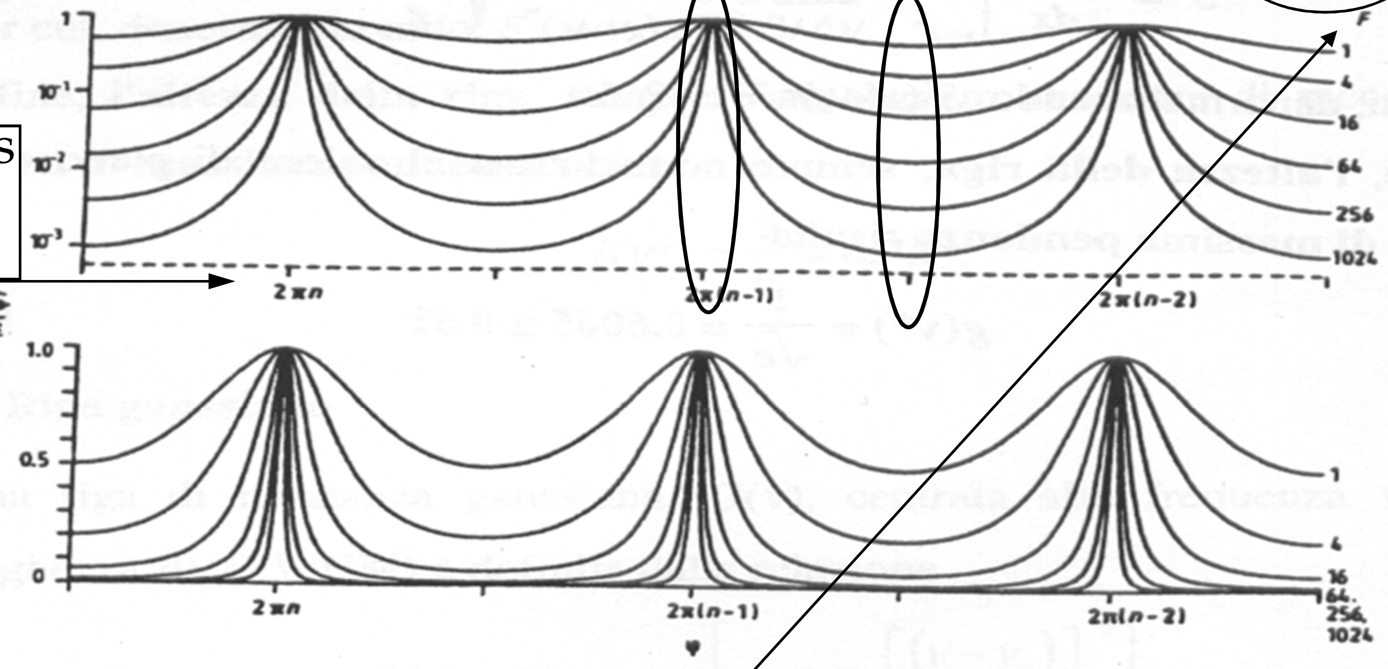
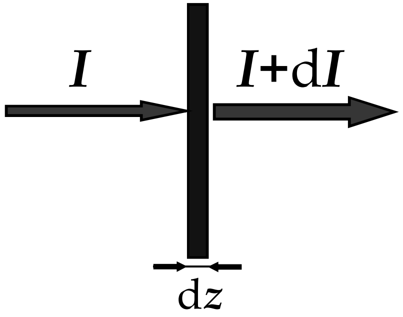


Fig. A.1 Profilo spettrale delle curve di Airy corrispondenti alla trasmissione in potenza di un interferometro Fabry-Perot. Il parametro F è uguale a $\pi\sqrt{R}/(1-R)$; la variabile φ, e quindi la frequenza ottica ν, varia linearmente sull'asse orizzontale.

Optical gain in an active medium *(bis)*

Amplification, per unit length, in the active medium



$$\frac{\mathrm{d}I}{\mathrm{d}z} = \sigma \Delta N \cdot I$$

For an active medium of length *l*:

$$\frac{I(l)}{I(0)} = G = \sigma \Delta N \cdot L$$ single-pass optical gain

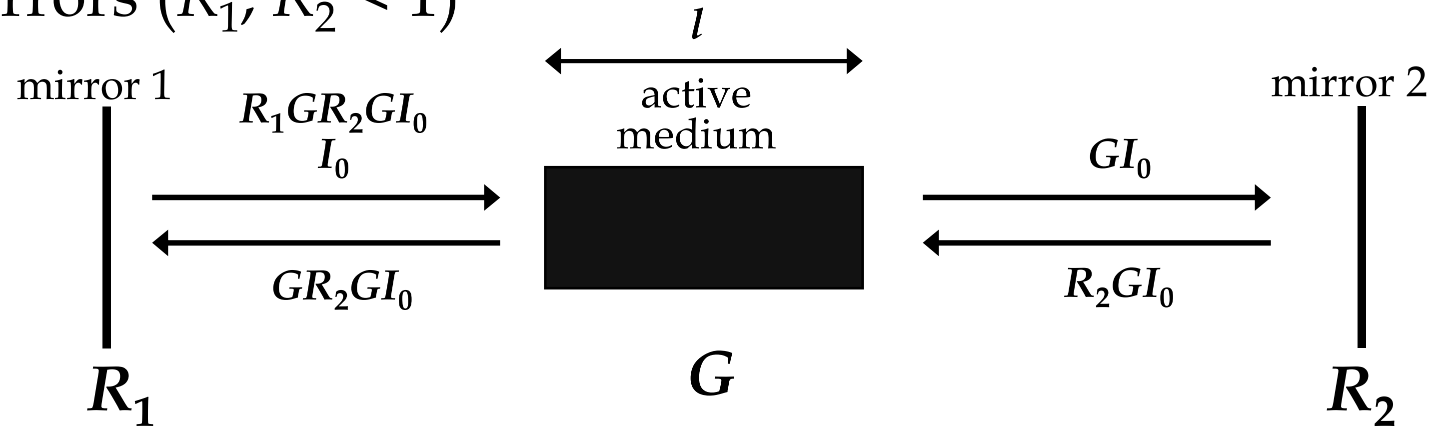
For <u>each pass</u> in the active medium the optical beam experiences an un <u>optical gain *G*</u> in intensity/power

Let’s find the value of <u>critical gain</u> (and critical inversion) allowing the <u>start of laser oscillation</u> in an active medium undergoing positive feedback

Threshold condition for laser action

The *round-trip* (double-pass) gain must equate the losses within the resonator (mirrors reflectivity, surfaces and materials crossed by the beam, diffraction).

Considering (ideal case) just the partial reflectivity of the mirrors (R_1, $R_2 < 1$)



in a *round-trip* it must be $R_1GR_2GI_0 = I_0 \;\Rightarrow\; G^2 = 1/(R_1R_2)$

$$\exp[2\sigma(N_2\text{-}N_1)l] = 1/(R_1R_2) \;\Rightarrow\; \boldsymbol{\sigma(N_2\text{-}N_1)l = (1/2)[-\ln(R_1) - \ln(R_2)] = \gamma}$$

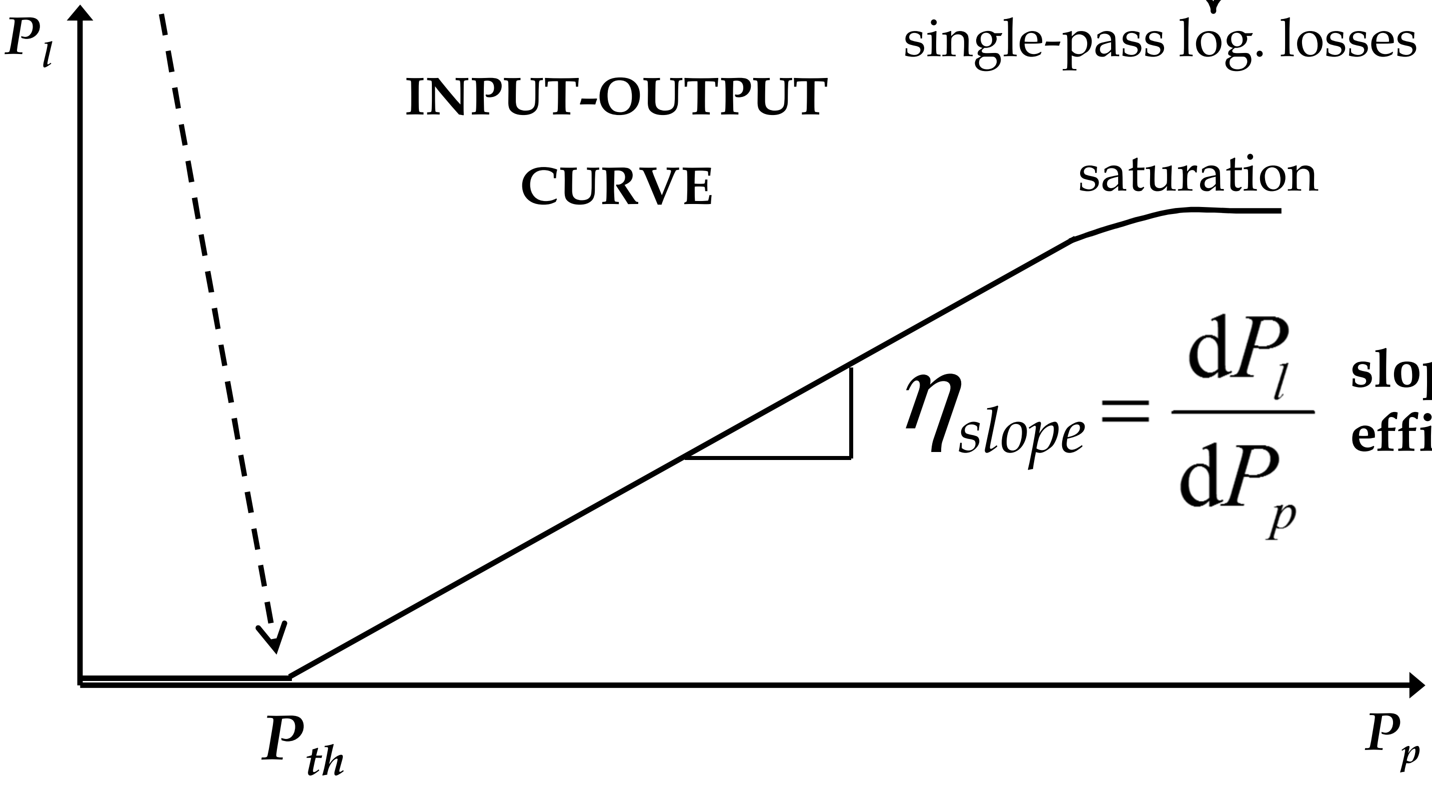
Critical inversion, threshold power and slope efficiency in a LASER

$\gamma=(1/2)[-\ln(R_1)-\ln(R_2)]$ log. losses

gain = losses

$\sigma(N_2-N_1)l = \gamma$ (threshold)

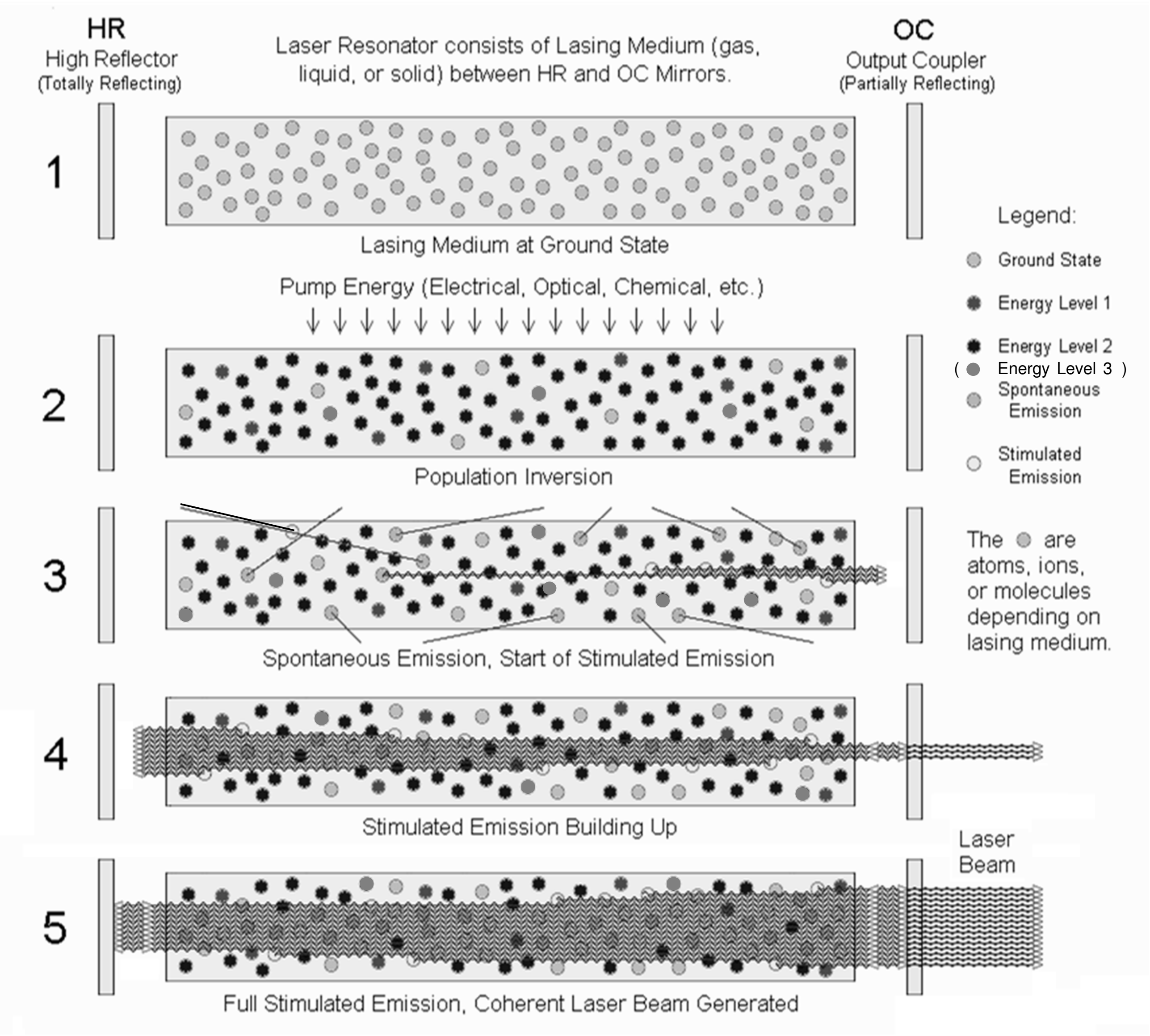
$$\left(N_2-N_1\right)_{th}=\frac{\gamma}{\sigma l} \quad \text{with } \underbrace{\gamma=-\frac{\ln R_1}{2}-\frac{\ln R_2}{2}=\frac{\gamma_1+\gamma_2}{2}}_{\text{single-pass log. losses } \gamma(1)}$$



$$\eta_{slope}=\frac{\mathrm{d}P_l}{\mathrm{d}P_p}$$

slope efficiency

Active medium, pumping, population inversion, laser action, optical feedback, laser oscillation



Elements of a LASER oscillator (*bis*)

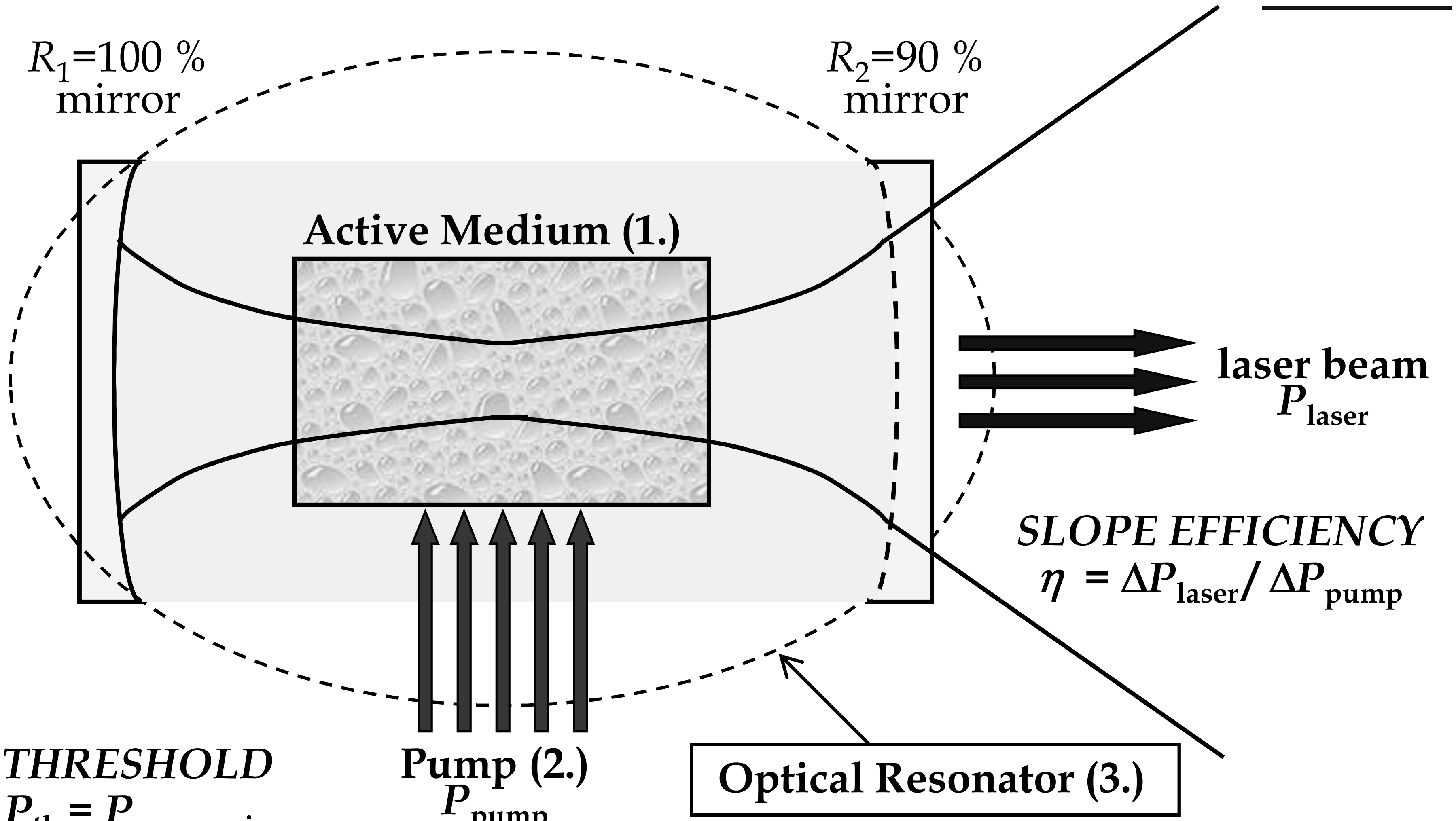
1. **Active MEDIUM**
atoms/ions/molecules: **energy levels**

2. **PUMP** mechanism **[**and **laser threshold]**
Energy transfer “exciting” the Active Medium achiving a **“population inversion”** in order to obtain an **optical gain**

3. **Optical RESONATOR**
system for **e.m. radiation confinement**

… now let’s see the STRUCTURE of a LASER …

Structure of a LASER oscillator



R_1=100 %
mirror

R_2=90 %
mirror

Active Medium (1.)

laser beam
P_{laser}

SLOPE EFFICIENCY
$\eta = \Delta P_{\text{laser}} / \Delta P_{\text{pump}}$

THRESHOLD
$P_{\text{th}} = P_{\text{pump,min}}$
for P_{laser}>0

Pump (2.)
P_{pump}

Optical Resonator (3.)

Colors are only for visual purpose …

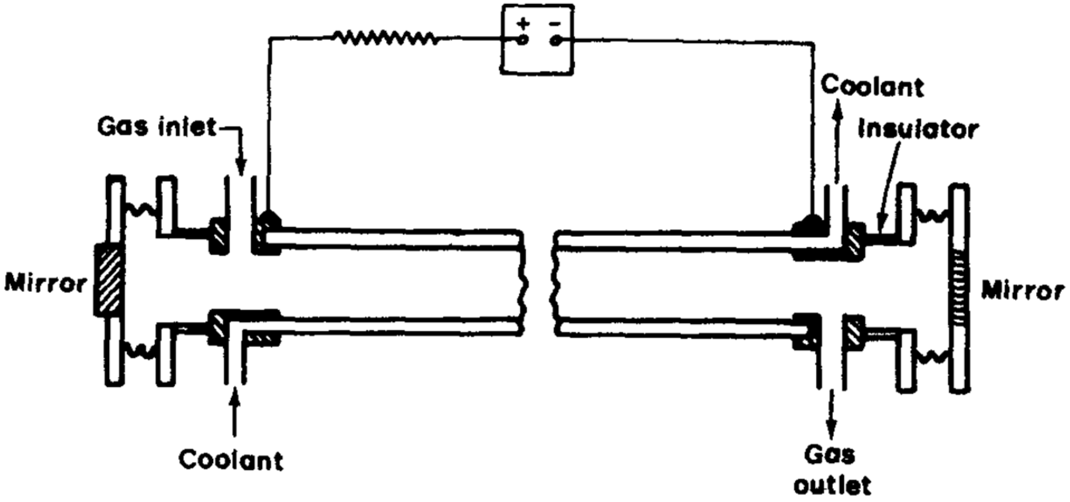
LASER Types (classification criteria)

1. Physical state and properties of the **active medium**:
   - **gas** LASERs
   - **colorant** (**liquid**) LASERs
   - **solid state** LASERs (in a crystal or amorphous host)
   - **semiconductor** LASERs **(**in a semiconductor; **Laser Diode or LD)**

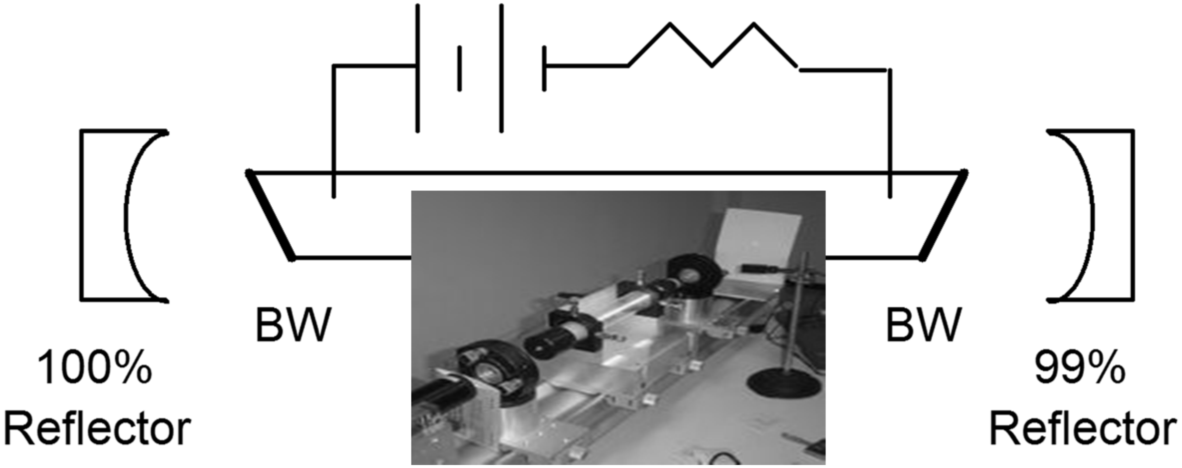
2. Emission **wavelength**
   - LASERs in the **IR**, **VIS**, UV, and X-ray

3. Operating **regime**
   - **CONTINUOUS WAWE (CW)** LASERs
     multi-mode, single-mode (long./trasv.), single-frequency
   - **PULSED** LASERs
     free-running, *Q-switching*, *mode-locking*

Gas LASERs (electrical discharge pump)



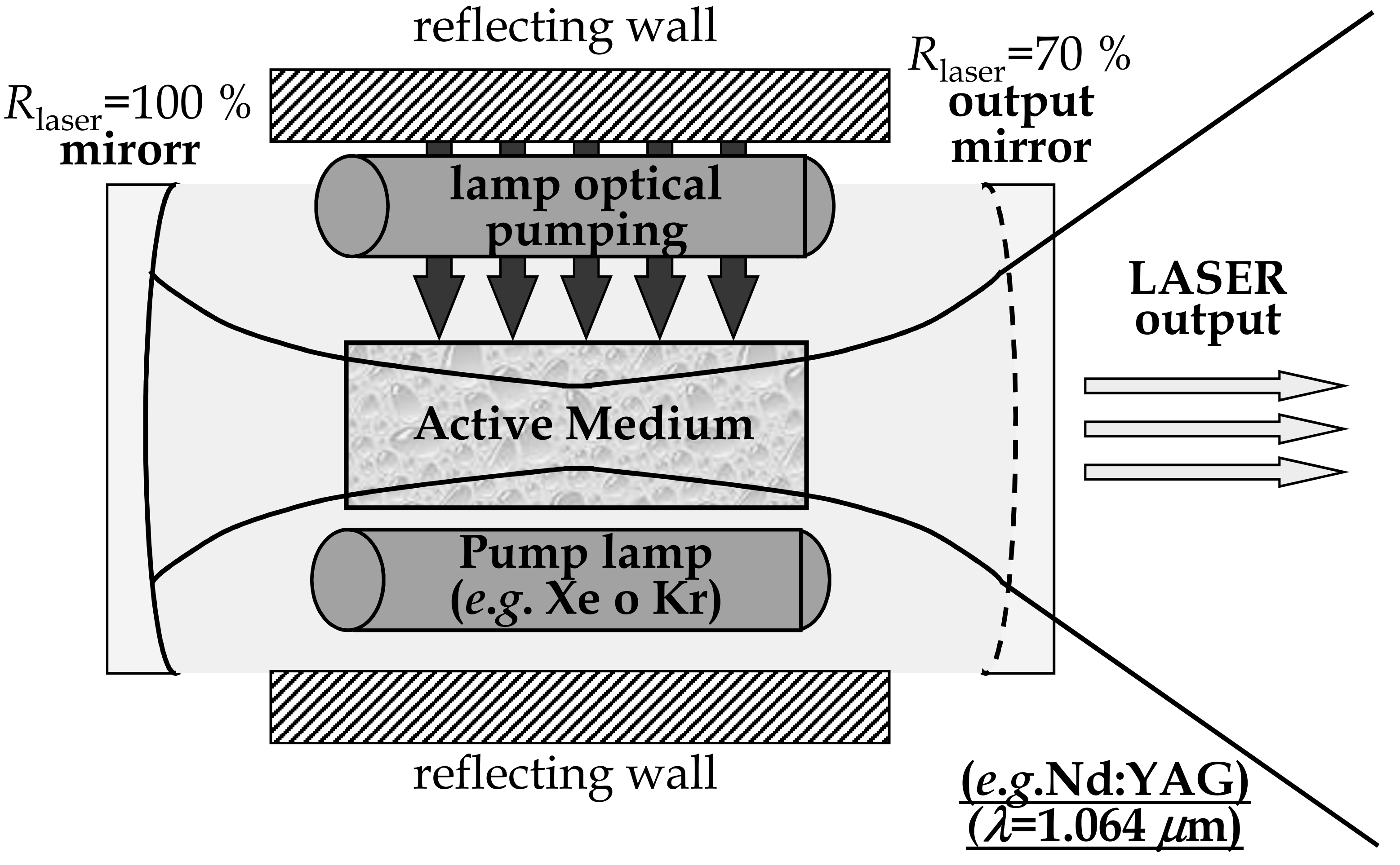
Flow tube
(CO_2)
λ = 10.6 µm (IR)
$P \approx$ kW



Sealed tube
(He-Ne)
(10 : 1)
λ = 632.8 µm (VIS)
$P \approx$ mW

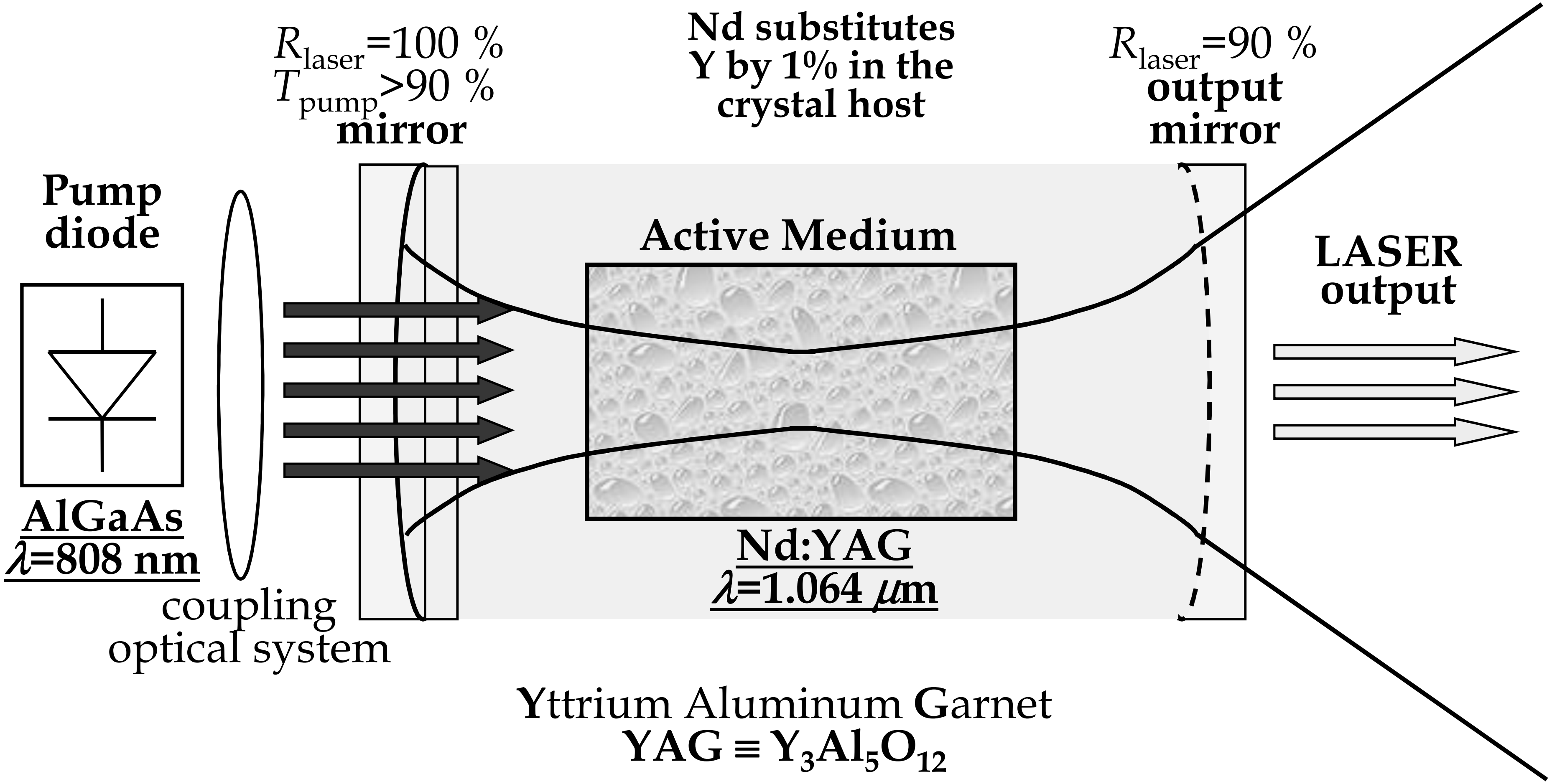
The electrical discharge excites (by electron-atom impact) the He atoms that transfer their excitation energy (*resonant energy-transfer*) to the **Ne atoms** finally **providing LASER action**

Solid-state LASERs (*side-pumping*)



Solid-state LASERs (*end-pumping*)

(specific example with Nd:YAG)



R_{laser}=100 %
T_{pump}>90 %
mirror

Nd substitutes Y by 1% in the crystal host

R_{laser}=90 %
output mirror

Pump diode

Active Medium

LASER output

AlGaAs
λ=808 nm

Nd:YAG
λ=1.064 μm

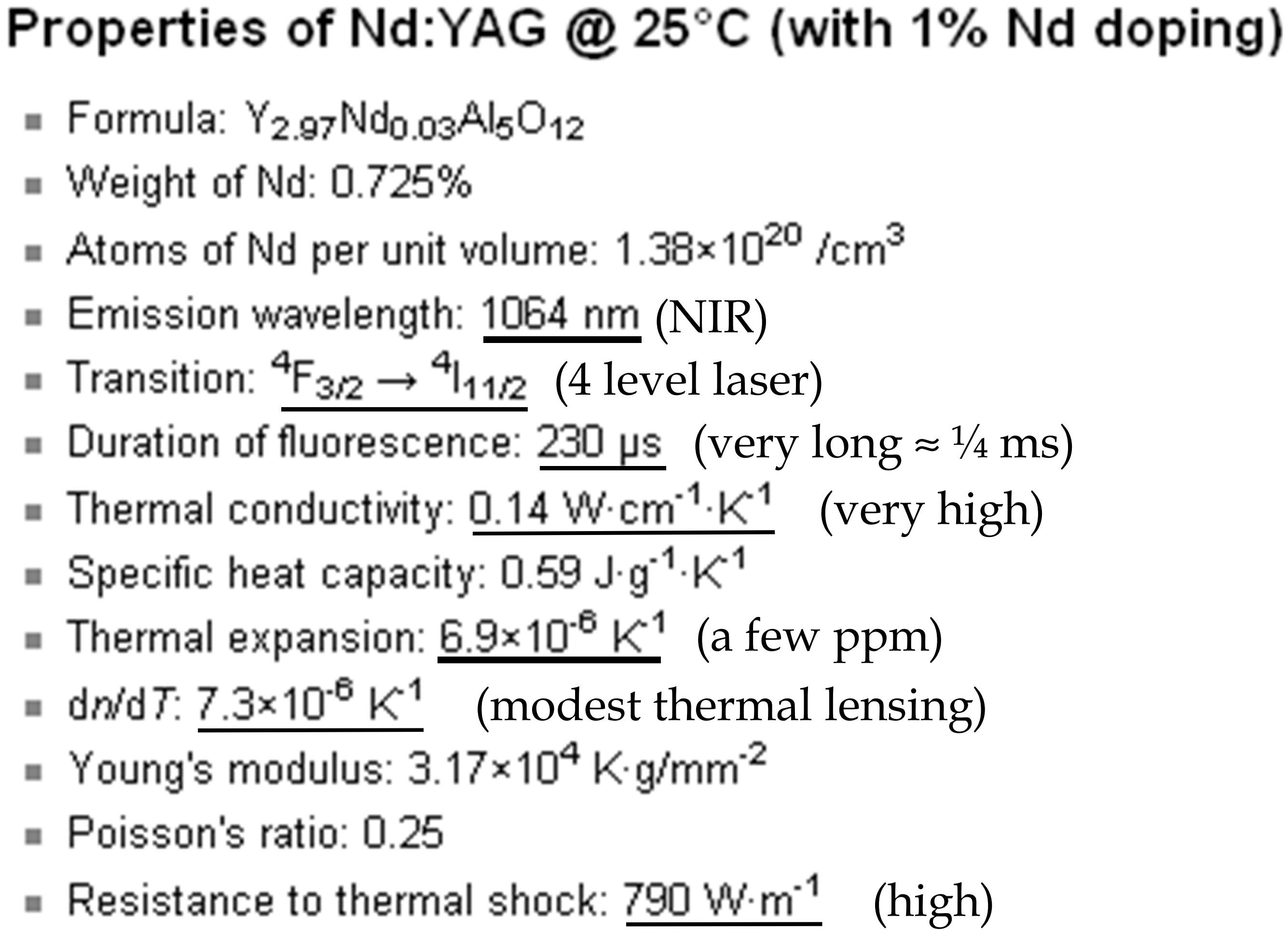
coupling optical system

Yttrium **A**luminum **G**arnet
YAG ≡ $Y_3Al_5O_{12}$

yttrium + alumina
($Y + Al_2O_3$)

Properties of the active mediumi

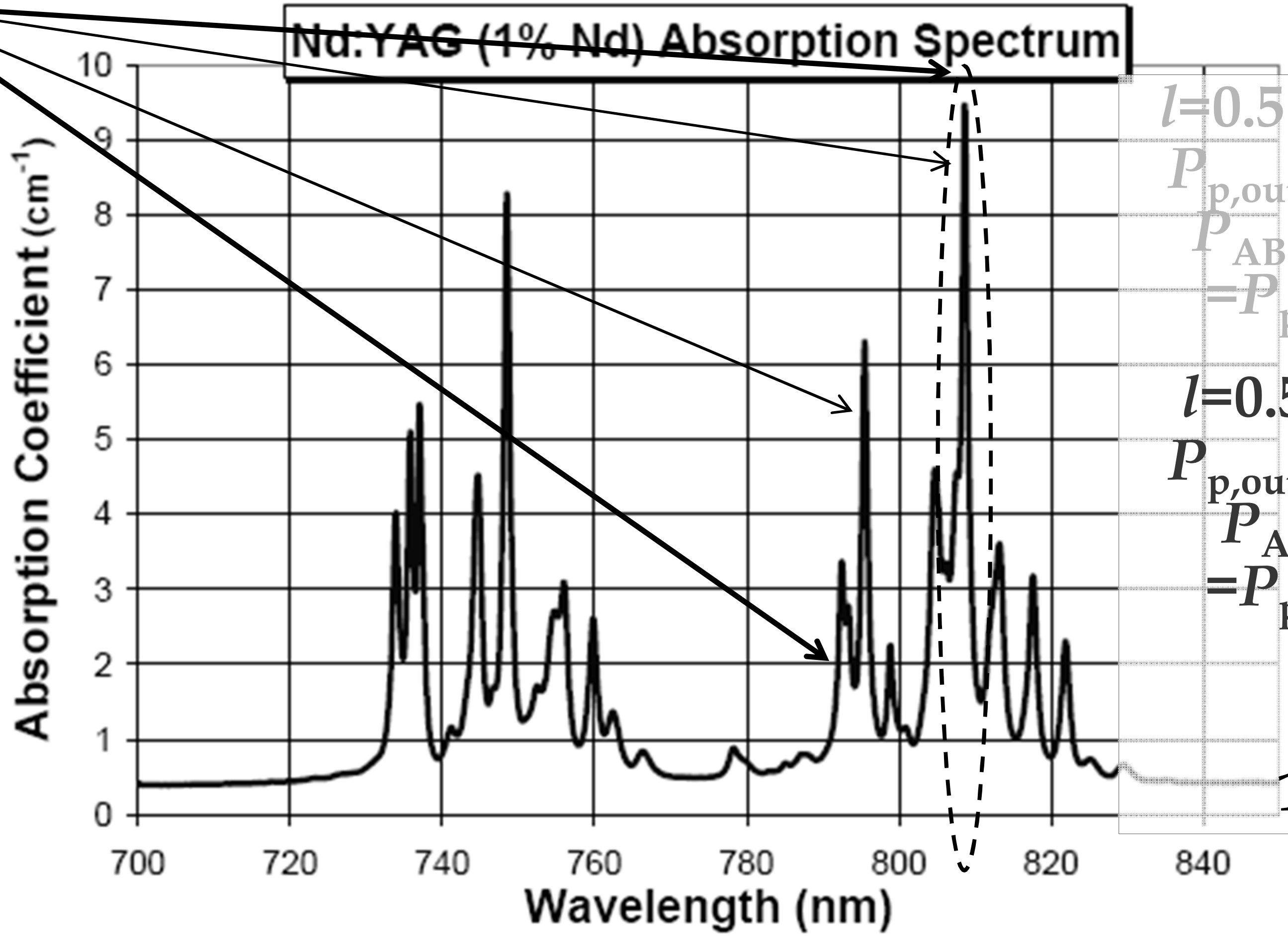
Nd:YAG: 1%-atomic =0.725%-weight)



Properties of Nd:YAG @ 25°C (with 1% Nd doping)

- Formula: $Y_{2.97}Nd_{0.03}Al_5O_{12}$
- Weight of Nd: 0.725%
- Atoms of Nd per unit volume: 1.38×10^{20} /cm^3
- Emission wavelength: 1064 nm (NIR)
- Transition: $^4F_{3/2} \rightarrow {}^4I_{11/2}$ (4 level laser)
- Duration of fluorescence: 230 μs (very long ≈ ¼ ms)
- Thermal conductivity: $0.14\ W \cdot cm^{-1} \cdot K^{-1}$ (very high)
- Specific heat capacity: $0.59\ J \cdot g^{-1} \cdot K^{-1}$
- Thermal expansion: $6.9 \times 10^{-6}\ K^{-1}$ (a few ppm)
- dn/dT: $7.3 \times 10^{-6}\ K^{-1}$ (modest thermal lensing)
- Young's modulus: $3.17 \times 10^4\ K \cdot g/mm^{-2}$
- Poisson's ratio: 0.25
- Resistance to thermal shock: $790\ W \cdot m^{-1}$ (high)

Light absorption in Nd:YAG



logarithmic
scale

$$P_{p,l} = P_{p,0} \exp(-\alpha l)$$

l=0.5 cm ; α=10 cm^{-1}
$P_{p,out} = P_{p,0} \exp(-5)$
P_{ABS}=99.3%$P_{p,0}$ =
=$P_{p,0}$ [1-exp (-5)]

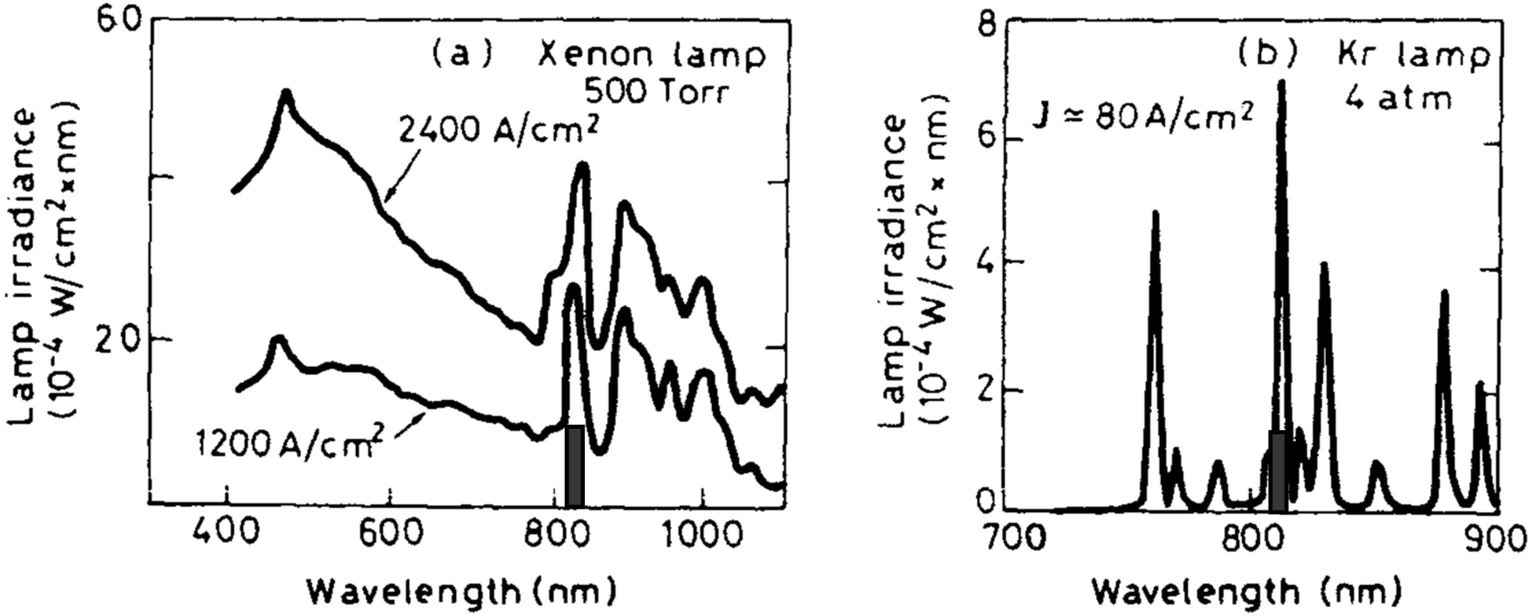
l=0.5 cm ; α=2 cm^{-1}
$P_{p,out} = P_{p,0} \exp(-1)$
P_{ABS}=63%$P_{p,0}$ =
=$P_{p,0}$ [1-exp (-1)]

1/5 in α
is not
1/5 in P_{ABS}

The absorption spectrum provides a strong **absorption peak at 808 nm**

Optical pumping: lamp vs diode

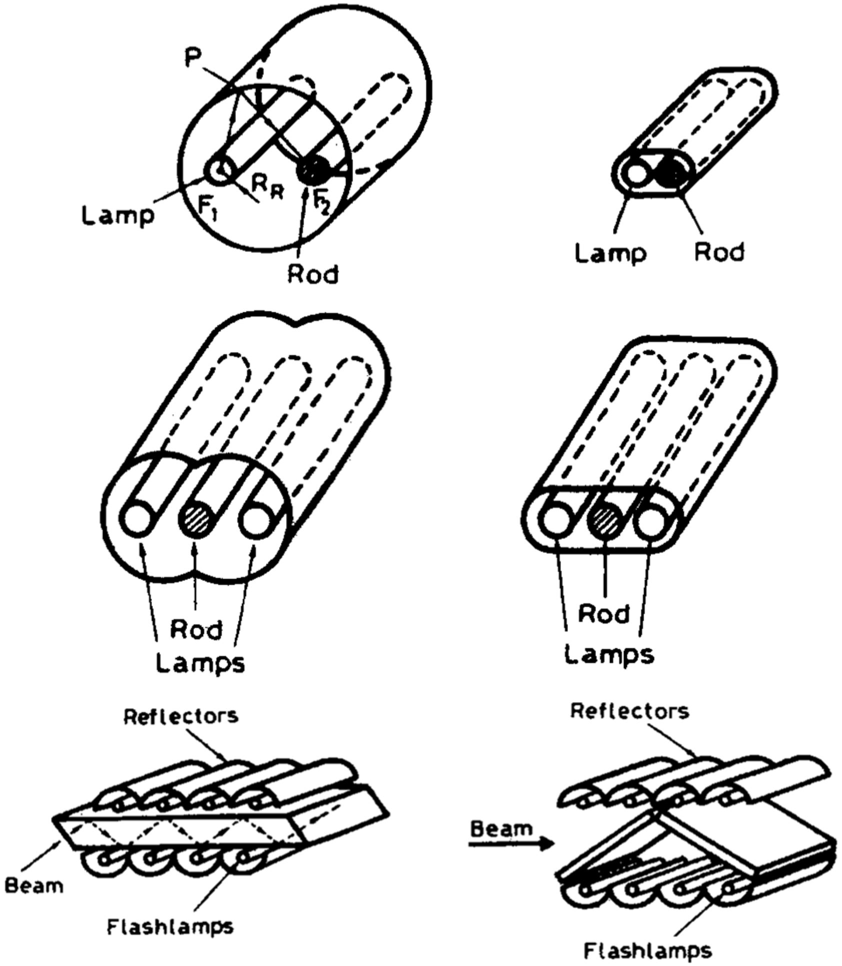
Comparison of emission spectra (lamps/LDs) for Nd:YAG pumping



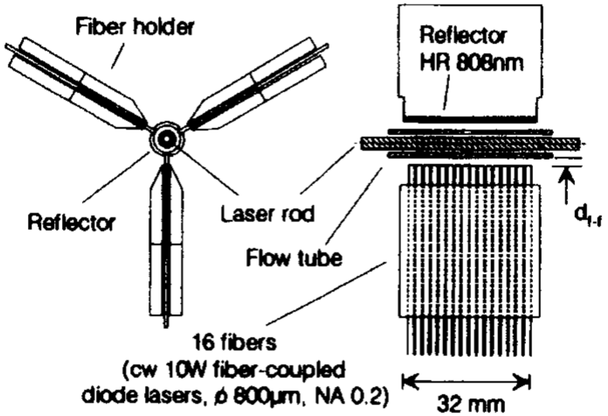
- The **spectral efficiency** of diode pumping [▮] ($\Delta\nu \sim 10$ nm) is much higher than for lamp pumping [—] ($\Delta\nu \sim 200 \div 500$ nm)
- Pump energy not usefully absorbed generates **excess heat** (→**thermal lensing** and also irreversible **damages**)

Pump geometry: lamp vs diode

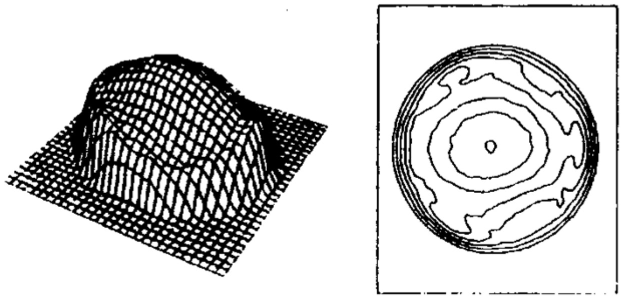
Transverse optical pumping
with one, two and more **lamps**



Transverse diode pumping
for an Nd:YAG laser rod

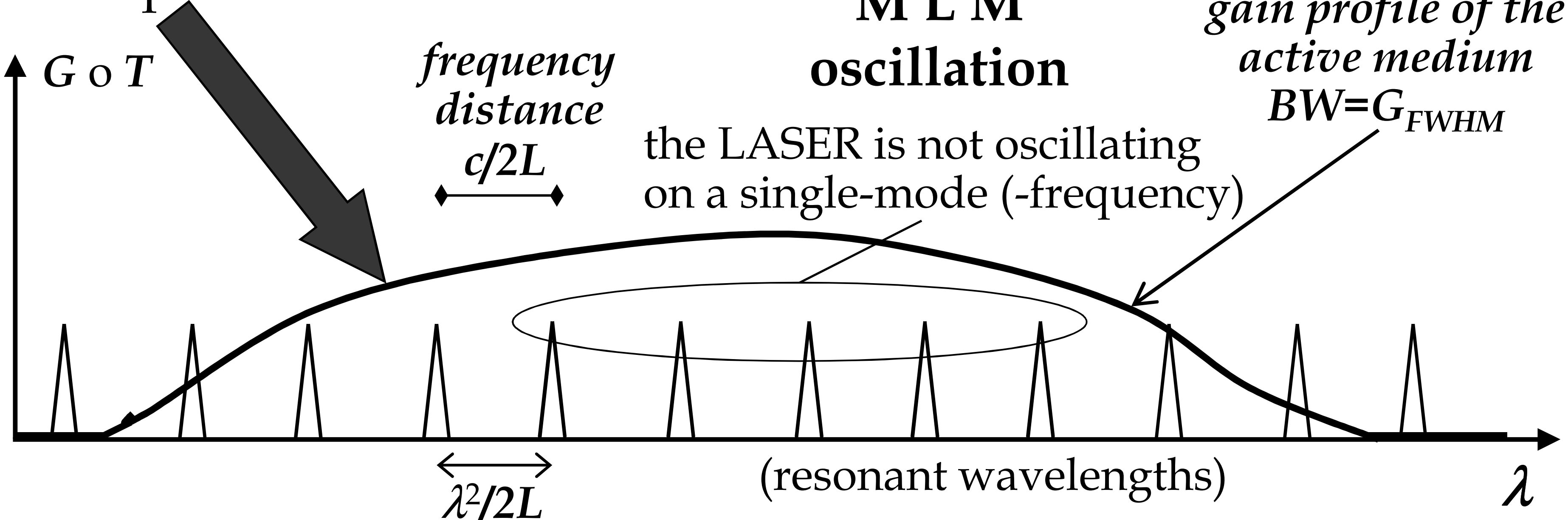


Pump spatial distribution
in the active medium



Pump: 150 W   LASER: 62 W CW TEM$_{00}$

Longitudinal Modes and Gain Bandwidth



energy levels
"dispersion"

G o T

frequency distance c/2L

M L M oscillation

the LASER is not oscillating
on a single-mode (-frequency)

gain profile of the active medium $BW=G_{FWHM}$

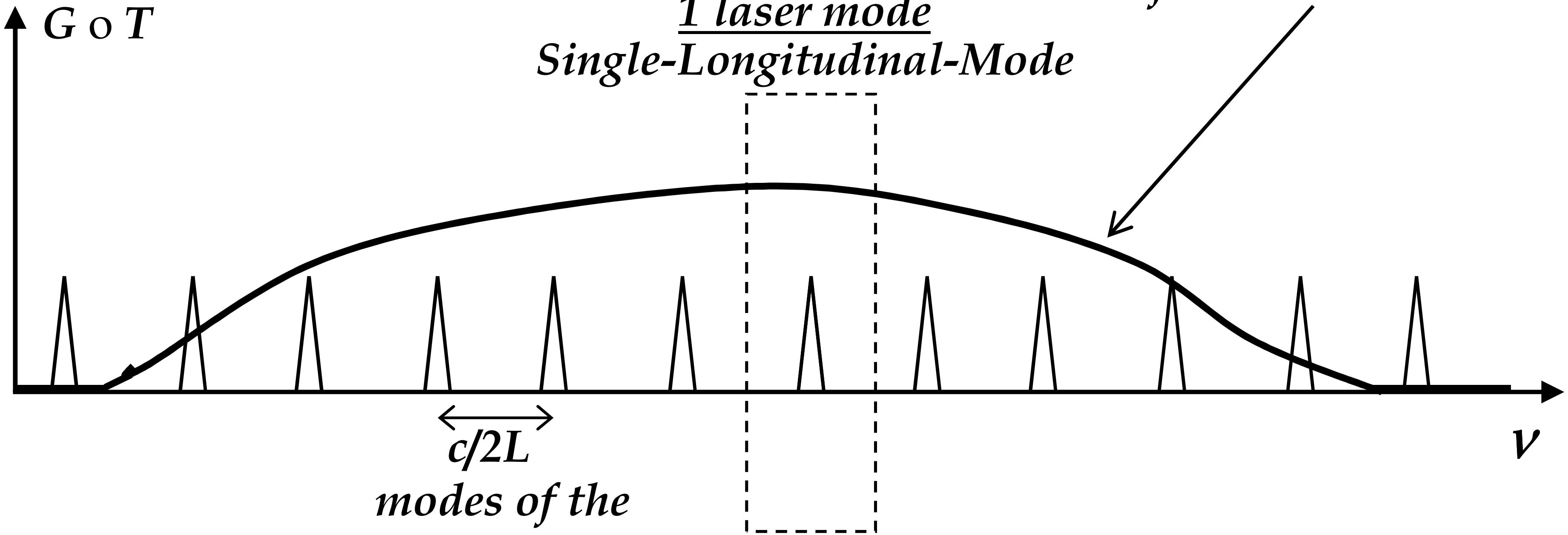
(resonant wavelengths)

λ

$\lambda^2/2L$
long. modes of the resonator

All longitudinal modes with "enough gain" oscillate simultaneously (MLM). Typically the LMs closer to the peak of the gain profile do oscillate at the same time.

SLM selection



S L M
oscillation
1 laser mode
Single-Longitudinal-Mode

gain profile of the active medium

$G \circ T$

ν

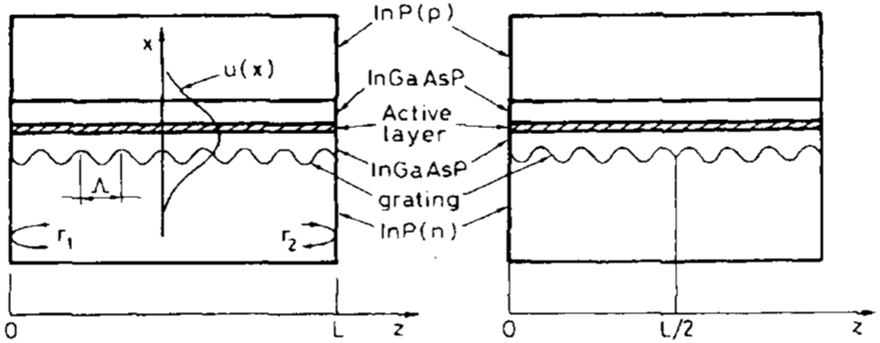
c/2L
modes of the resonator

Optical Filter
(band-pass)
with $\Delta\nu_c < c/2L$

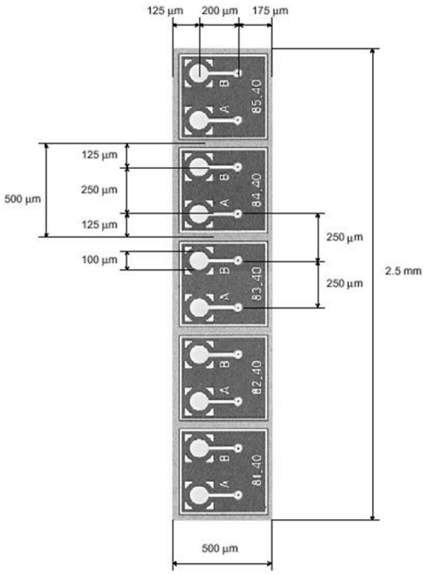
example: Fabry-Perot etalon
chosen with $FSR > G_{FWHM}$

Single-mode semiconductor LASERs

Distributed Feed-Back (DFB)

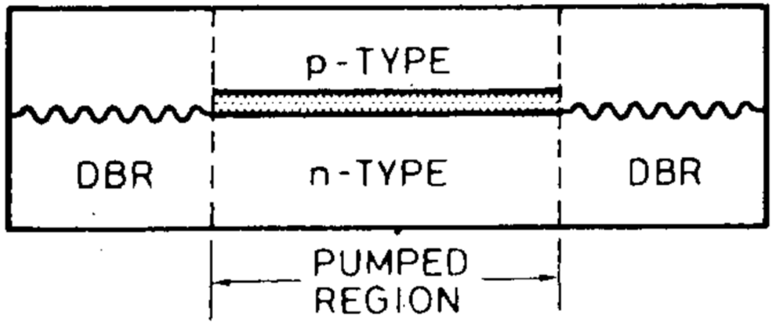


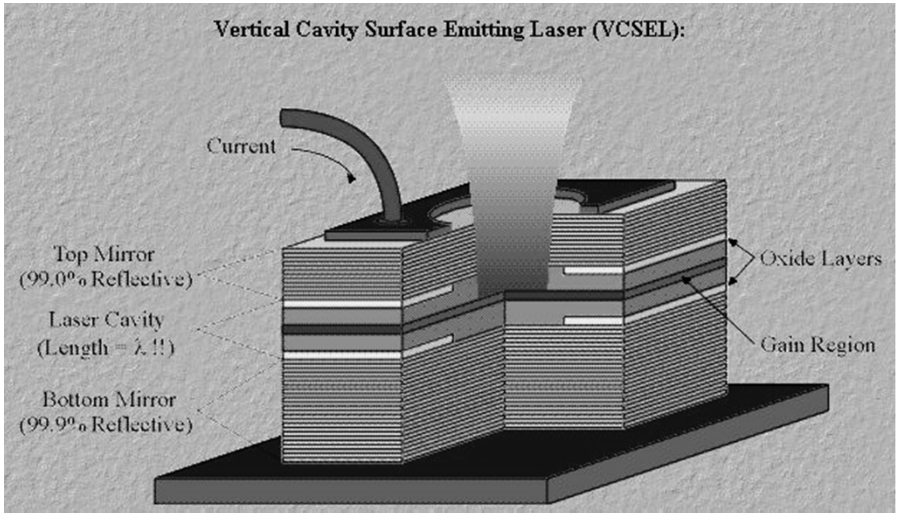
~~FP~~
less
used



VCSEL

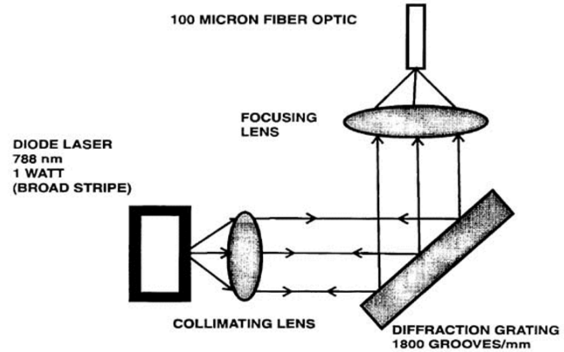
Distributed Bragg Reflector (DBR)

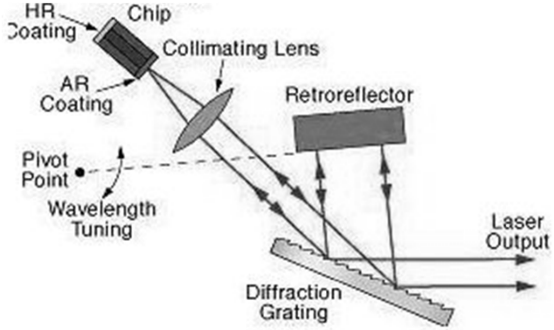




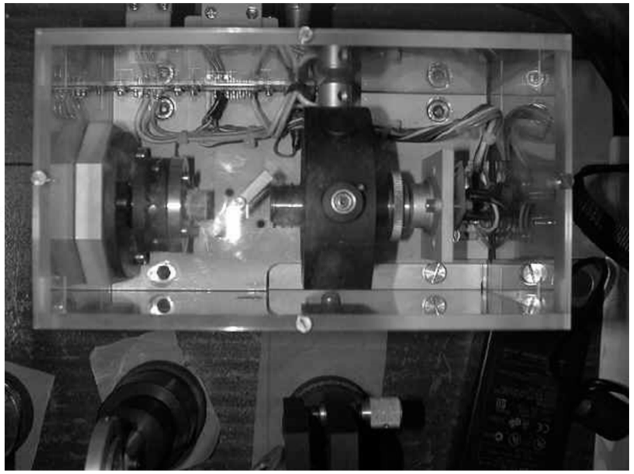
SLM due to "spectral filtering" of the monolithic optical resonator

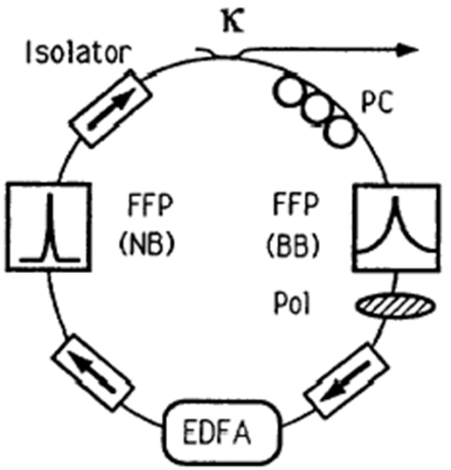
1.5 μm *narrow-linewidth* LASERs



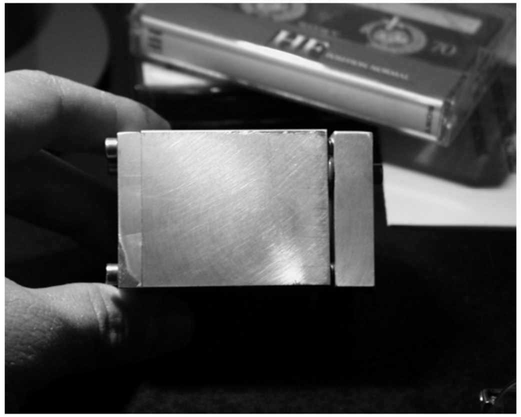


Extended Cavity LD (ECLD)

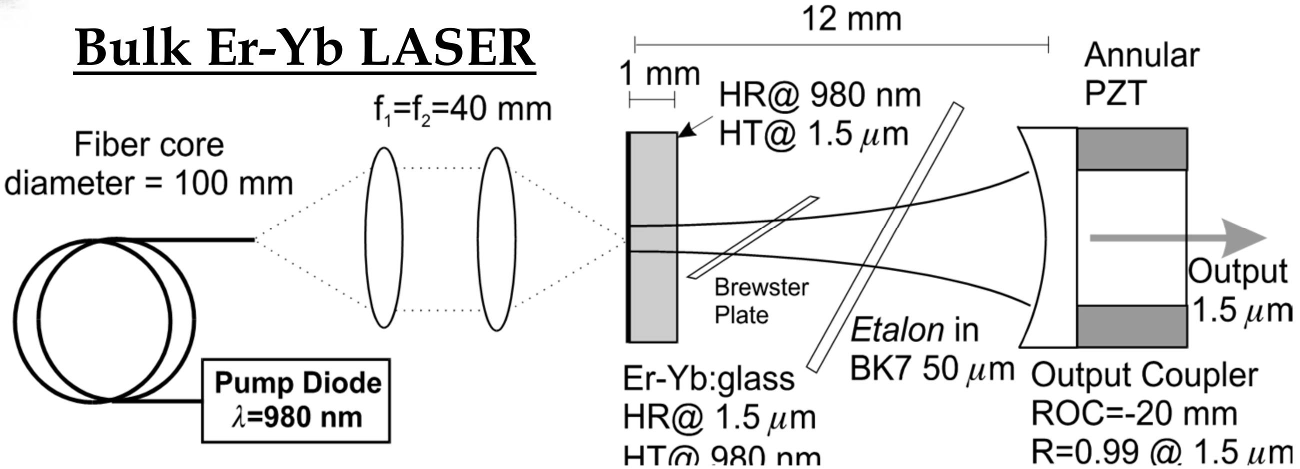




Er fiber LASER

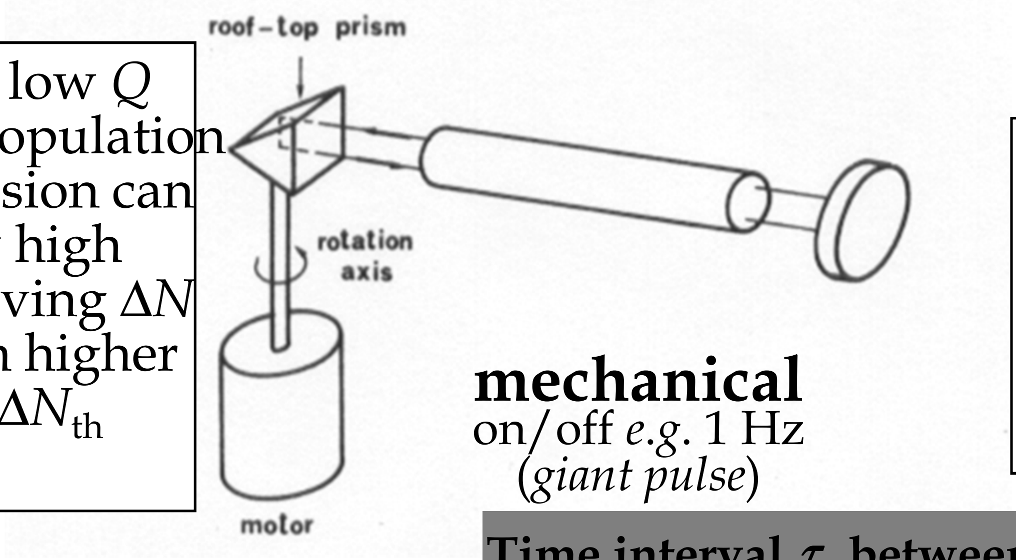


Bulk Er-Yb LASER



Pulsed LASERs : *Q-switching*

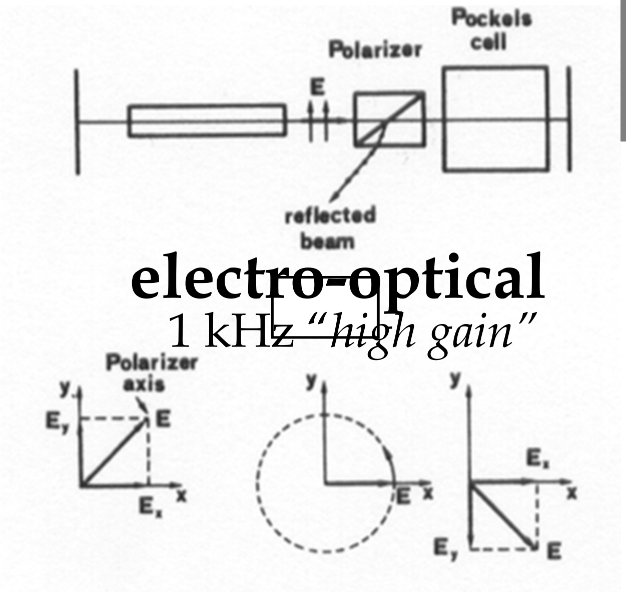
With low Q the population inversion can grow high achieving ΔN much higher than ΔN_{th}



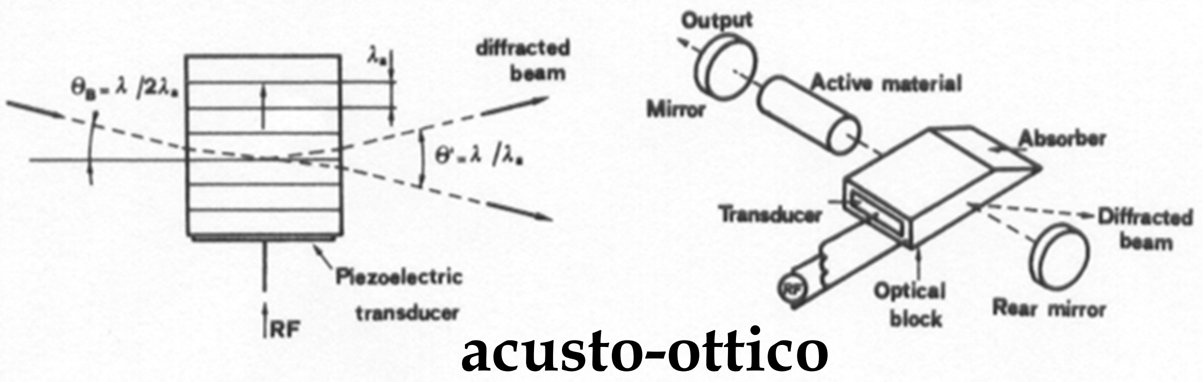
mechanical
on/off *e.g.* 1 Hz
(*giant pulse*)

All the pump energy accumulated in the active medium is released, in a short time, when the resonator is "aligned" (high Q condition)

Time interval τ_p between pulses: depends on the *switch*
Pulse duration $\Delta\tau_p$: depends on active medium (≈10 ns)
***duty cycle* ($\Delta\tau_p/\tau_p$) is low ⇒ <u>peak power is high (≈MW)</u>**



electro-optical
1 kHz *"high gain"*



acusto-ottico
10-100 kHz *"low gain"*

Pulsed LASERs: *mode-locking*

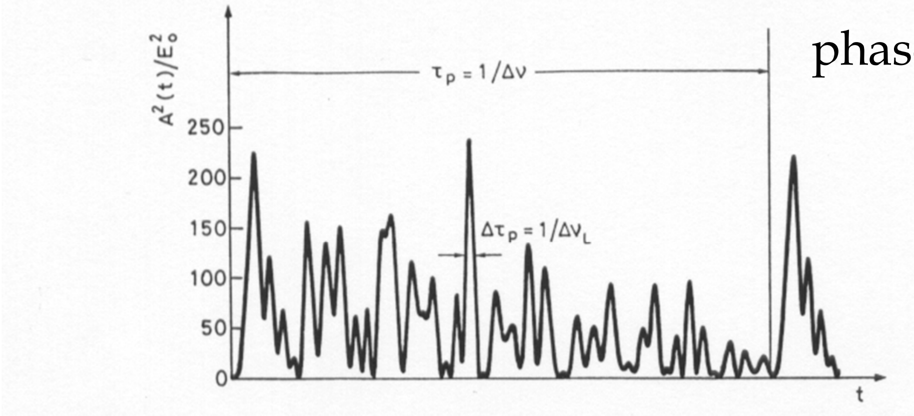


FIG. 8.15. Example of time behavior of the squared amplitude of the total electric field, $|A(t)|^2$, for the case of 51 oscillating modes, all with the same amplitude E_0 and with random phases.

phase-locked longitudinal modes

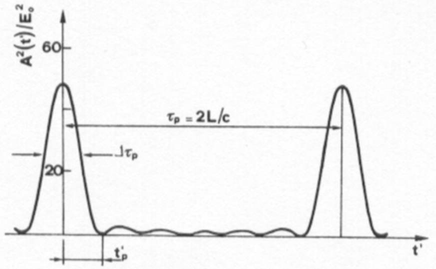
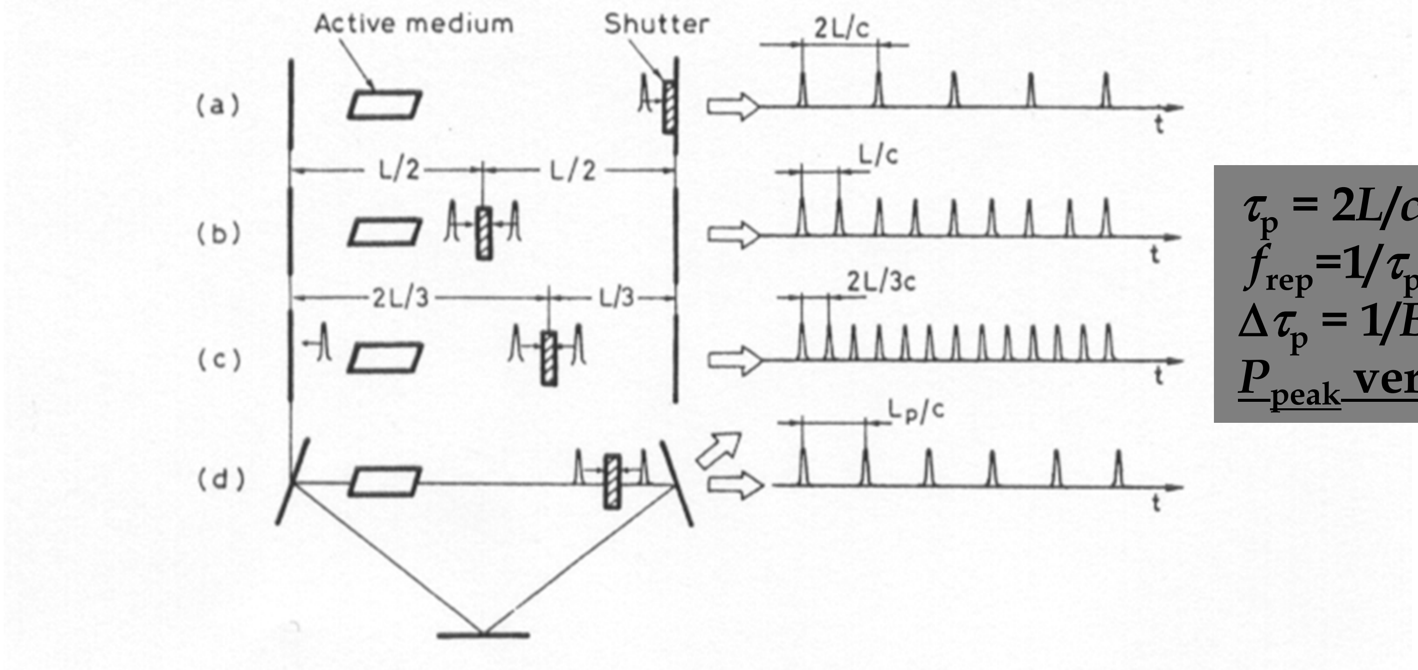


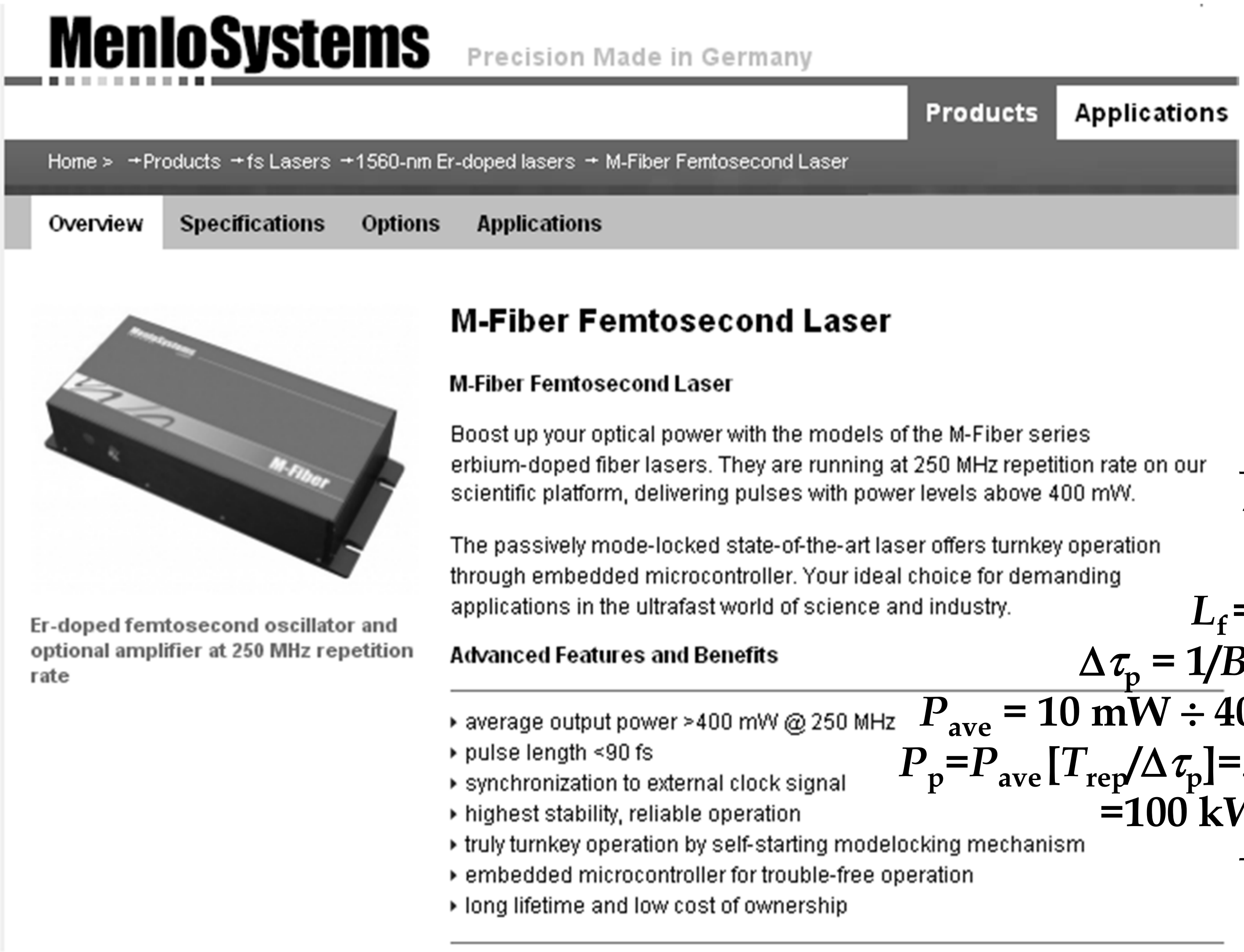
FIG. 8.17. Time behavior of the squared amplitude of the electric field for the case of seven oscillating modes with locked phases and equal amplitudes, E_0.



1.5 m ÷1.5 cm

$\tau_p = 2L/c$ (*round trip*)
$f_{rep} = 1/\tau_p$ (100 MHz ÷ 10 GHz)
$\Delta\tau_p = 1/B_{laser}$ (10 ps ÷ 100 fs)
$\underline{P_{peak}}$ very high (up to >GW)

Femtosecond LASER (*mode locking*)



Er-doped femtosecond oscillator and optional amplifier at 250 MHz repetition rate

M-Fiber Femtosecond Laser

M-Fiber Femtosecond Laser

Boost up your optical power with the models of the M-Fiber series erbium-doped fiber lasers. They are running at 250 MHz repetition rate on our scientific platform, delivering pulses with power levels above 400 mW.

The passively mode-locked state-of-the-art laser offers turnkey operation through embedded microcontroller. Your ideal choice for demanding applications in the ultrafast world of science and industry.

Advanced Features and Benefits

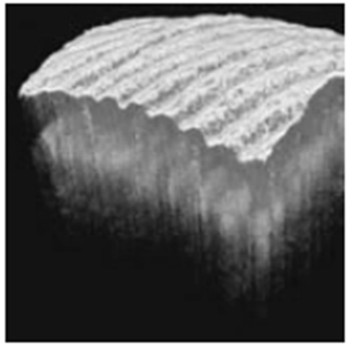
- average output power >400 mW @ 250 MHz
- pulse length <90 fs
- synchronization to external clock signal
- highest stability, reliable operation
- truly turnkey operation by self-starting modelocking mechanism
- embedded microcontroller for trouble-free operation
- long lifetime and low cost of ownership

$\tau_p = L_f/c$ (round *trip*)
$f_{rep} = 1/\tau_p$ (250 MHz)
$L_f = \tau_p \cdot c = c/f_{rep} = 1.2$ m
$\Delta\tau_p = 1/B_{laser}$ (<90 fs *e.g.* 80 fs)
$P_{ave} = 10$ mW ÷ 400 mW (*e.g.* 200 mW)
$P_p = P_{ave}[T_{rep}/\Delta\tau_p] = 200$ mW [4 ns/80 fs]=
=100 kW (with $P_{elet} = 100$ W)

Applications of femtosecond LASERs

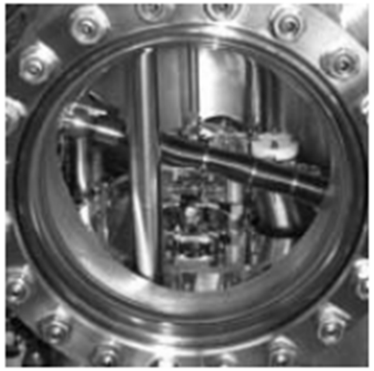
Medical Research

Ultrafast lasers open up new possibilities in the medical technology of micro surgery. They interact with matter in a way that is fundamentally different from all other lasers, e.g. providing the capability to precisely cut three-dimensional structures in the tissue volume. When deployed at lower, non-ablative energy levels, ultrafast light can trigger molecular and cellular phenomena with broad implications for medical treatments.



Optical Coherence Tomography

Optical coherence tomography (OCT) is an optical signal acquisition and processing method allowing extremely high-quality, micrometer-resolution and three-dimensional images within optical scattering media (e.g. biological tissue). Axial resolution of an OCT system is inherently connected to the probe light bandwidth. Recent developments have shown that ultra wide spectra can be generated when small core diameter fibers are irradiated by femtosecond pulses. A supercontinuum is produced by highly non-linear effects within a long interaction region, confined by the waveguide.

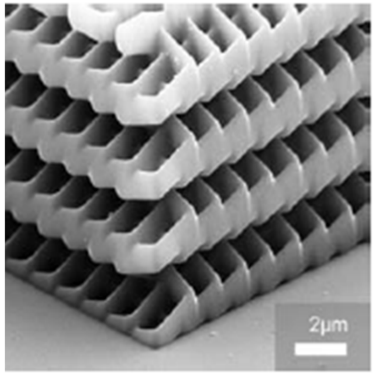


Spectroscopy

The methods of high resolution spectroscopy as well as time resolved laser spectroscopy have added significantly to our understanding of atoms and molecules as well as their interaction among each other. E.g. atomic and molecular elementary reactions, such as molecular oscillations, chemical reactions and the formation of transitional stages take place in a period of femtoseconds. To directly observe, analyze or even manipulate these phenomena ultrafast lasers are adequate tools to provide durations on the same time scale as elementary reactions.

Frequency Metrology

Optical frequency combs revolutionized the frequency metrology in the last years as they benefit from the robustness and reliability of ultrafast fiber lasers. These lasers create highly correlated light pulses that have a spectrum that consists of an evenly spaced frequency comb of hundreds of thousands of sharp spectral lines. The patented frequency comb technology has received highest recognition with the award of the Nobel Prize in Physics 2005 to Prof. Theodor W. Hänsch, co-founder of Menlo Systems. To this day, the comb systems are the most precise measurement tool offering 14 digits resolution.

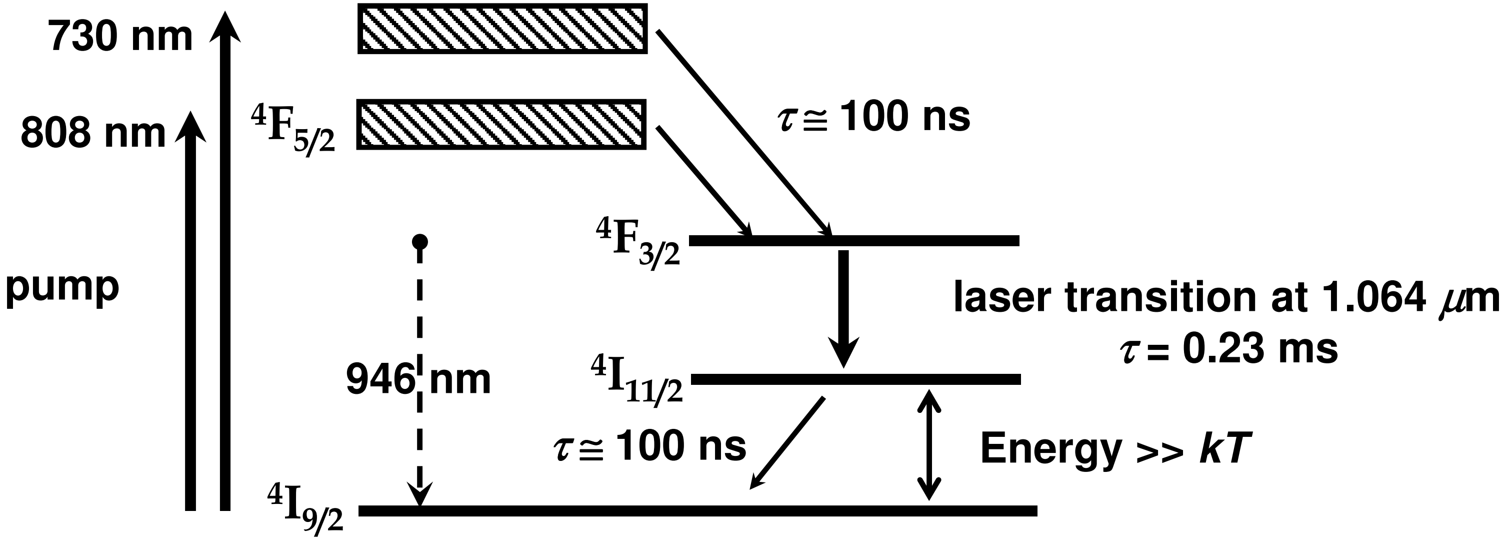


Micromachining

When micro material processes permit only highest quality standards, lowest production tolerances and best material requisitions, the ultrafast laser is generally applied. Applications for these lasers range from high-precision ablation of metals to direct laser writing of photosensitive materials in three dimensions.

Properties of the Nd:YAG LASER

- **Energy levels of the ion Nd^{3+} in YAG crystal ($Y_3Al_5O_{12}$)**



- **Doping in the order of 1-2 % (Nd^{3+} substituting Y^{3+})**
- **Gain bandwidth $\Delta\nu$ = 125 GHz (~0.4 nm) [40× in glass]**
- **Slope efficiency 3÷5 % (lamps) and >20 % (diodes)**

Pulsed Nd:YAG LASER

$$\boxed{\lambda\nu = c \quad \Rightarrow \quad \frac{\Delta\lambda}{\lambda} = -\frac{\Delta\nu}{\nu}}$$

$$\boldsymbol{\lambda \sim 1\ \mu\text{m} \ \ \text{and} \ \ \nu \sim 300\ \text{THz}}$$

$$\boldsymbol{\Delta\lambda_{\text{YAG}} \sim 0.4\ \text{nm} \ \ \text{e} \ \ \Delta\lambda_{\text{glass}} \sim 40\times\Delta\lambda_{\text{YAG}} \sim 16\ \text{nm}}$$

$$\Delta\nu_{\enclose{circle}{\text{YAG}}} = -\frac{\Delta\lambda}{\lambda}\nu \approx \frac{0.4\ \text{nm}}{1064\ \text{nm}}\cdot 300\ \text{THz} \cong 120\ \text{GHz} \approx \enclose{circle}{125\ \text{GHz}}$$

$$\Delta\nu_{\enclose{circle}{\text{glass}}} = -\frac{\Delta\lambda}{\lambda}\nu \approx \frac{16\ \text{nm}}{1064\ \text{nm}}\cdot 300\ \text{THz} \cong 4800\ \text{GHz} \approx \enclose{circle}{5\ \text{THz}}$$

Operating in a
mode-locking regime $\Rightarrow$

$$\enclose{circle}{\Delta\tau_{\text{p,YAG}}} \approx \frac{1}{\Delta\nu_{\text{YAG}}} \approx \enclose{circle}{8\ \text{ps}}$$

$$\enclose{circle}{\Delta\tau_{\text{p,glass}}} \approx \frac{1}{\Delta\nu_{\text{glass}}} \approx \enclose{circle}{200\ \text{fs}}$$

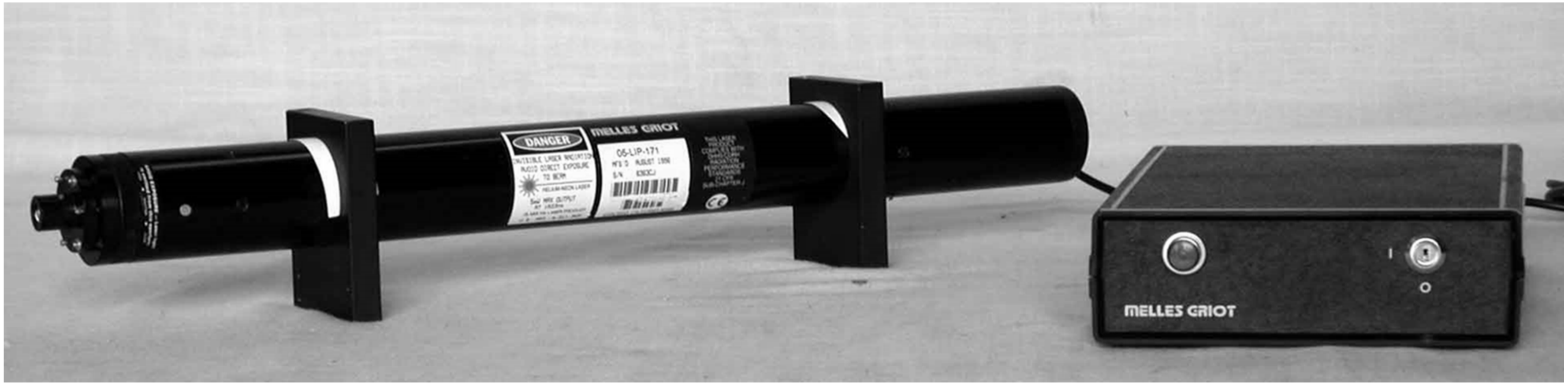
Main properties of typically-used LASERs

Laser	λ (μm)	P (W)	Dimension (m)	Efficiency η (%)	Cost (€)
He-Ne	0.632 (rosso)	10^{-3}-10^{-2}	0.1-1	0.1	100-2000
Nd:YAG	1.064	200 (CW) 10^{7} (peak)	1 0.1	1-10 33	50000 10000
CO_2	10	10^{4} (CW) 10^{7} (peak)	1	10-20	50000
Semiconductor	0.45-1.6	10^{-3}- 1	10^{-3}	50	10-10000

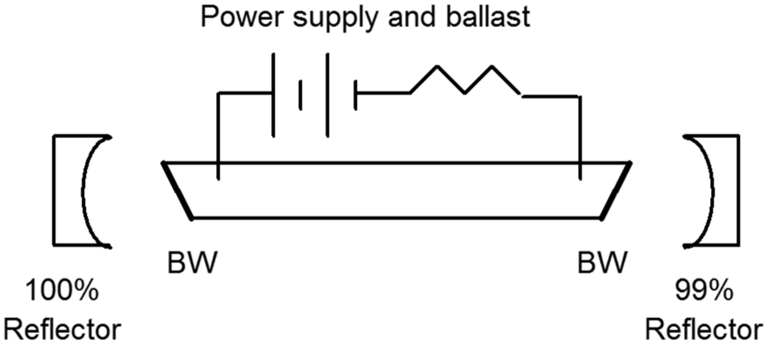
diode-pumped

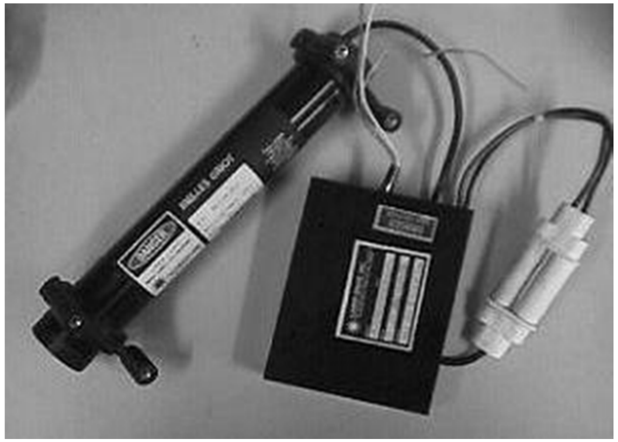
P_p=10^9 W in *mode-locking*

Example of “typical” LASER: He-Ne

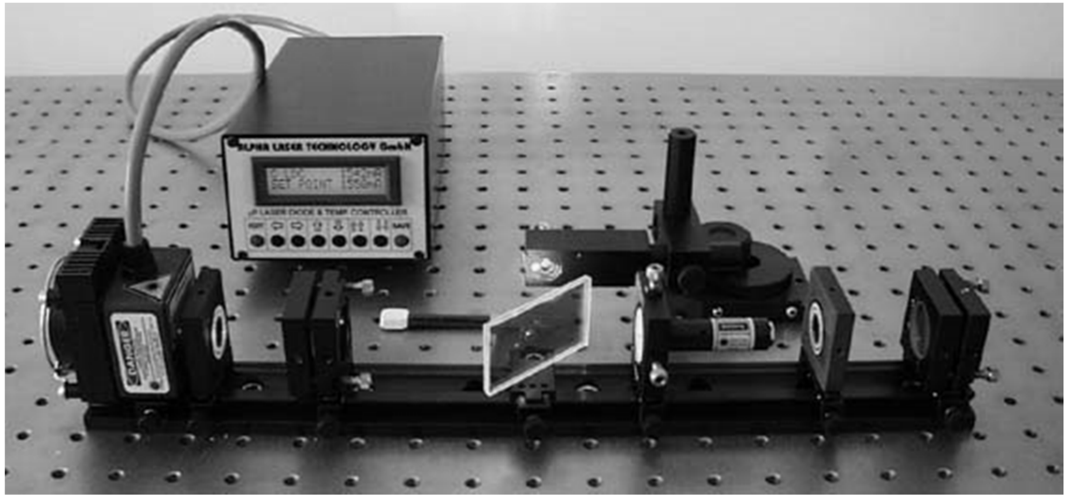


He-Ne Laser System





Example of “typical” LASER: Nd:YAG 2×



An ultra bright pointer is now on the market [class IIIA] (~5 mW at the green 532 nm wavelength): an intracavity frequency-doubled Nd:YVO_4 laser with blocked IR.