

Scuola di Dottorato Leonardo da Vinci – a.a. 2012/13

LASER: CARATTERISTICHE, PRINCIPI FISICI, APPLICAZIONI

Version 4 – July 13 – <http://www.df.unipi.it/~fuso/dida>

Part 5

Pumping and amplification in the active medium

OUTLOOK

- We have seen that a quantum system can provide with amplification if population is inverted
- We have seen as well that inversion of population cannot be achieved in a “closed” two level system
- The problem is now to find suitable methods to get inversion of population
 - pumping** as a mean to couple with external energy and obtain inverted population
 - rate equations with pumping included
 - example of master equations for a pumped three level system
 - practical methods to achieve pumping and kinds of lasers (classified according to pumping methods)*

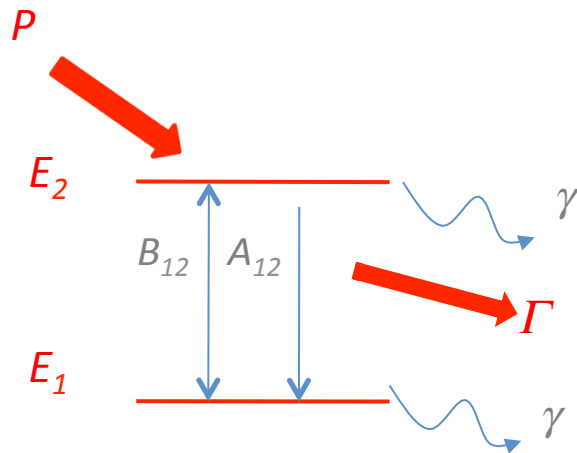
Main objective: to show how inversion of population can be achieved and the light amplification exploited

Additional objective: to start playing with different classes of practical laser systems and their main features

EXTERNAL PUMPING IN A TWO LEVEL SYSTEM

The system must be driven out of equilibrium in order to have inversion of population
→ this is called **PUMPING**

The mathematical treatment of a two level system with pumping is similar to what previously seen (but for some minor differences)



Added to the rate equation system:

- Pumping rate P (assumed as constant)
- Photon loss rate Γ

Note; the photon loss rate is explicitly mentioned as a separate process (also relaxation and spontaneous emission are losses for the photons in the medium) because photons *must be extracted from the medium* in order for the laser radiation to be useful! (we'll see more)

Assumptions (already seen):

- $g_1 = g_2 \rightarrow B_{12} = B_{21} = B$ (abs/stim em)
- $\gamma_1 = \gamma_2 = \gamma$ (relaxation rate)
- $A_{21} = A$ (spont em)

Here introduced:

- F : photon density in the medium $\rightarrow u_\nu = Fh\nu$

RATE EQUATIONS WITH (CONSTANT) PUMPING

$$\begin{aligned}\frac{dN_2}{dt} &= P - BFh\nu N_2 + BFh\nu N_1 - AN_2 - \gamma(N_2 - N_2^0) \\ \frac{dN_1}{dt} &= BFh\nu N_2 - BFh\nu N_1 + AN_2 - \gamma(N_1 - N_1^0) \\ \frac{dF}{dt} &= BFh\nu N_2 - BFh\nu N_1 - \Gamma F\end{aligned}$$

Note: valid only in the presence of P

$$\begin{aligned}\frac{d\Delta N}{dt} &= P - 2BFh\nu\Delta N - 2AN_1 - \gamma(\Delta N - \Delta N^0) \\ \frac{dF}{dt} &= BFh\nu\Delta N - \Gamma F\end{aligned}$$

Pumping can lead to inversion of population:

$$\Delta N_{staz} = \frac{P + \gamma\Delta N^0 - 2AN_2}{2BFh\nu + \gamma} \overset{\Delta N^0 \approx -N_1}{\sim} \frac{P - \gamma N_1 - 2AN_2}{2BFh\nu + \gamma}$$

$\Delta N > 0 \iff P > 2AN_2 + gN_1$
Pumping, if larger than some threshold, can effectively lead to $\Delta N > 0$

Density of photons (i.e., e.m. energy):

$$\frac{dF}{dt} = 0 \iff \Delta N_{staz} = \Delta N_{thr} = \frac{\Gamma}{Bh\nu}$$

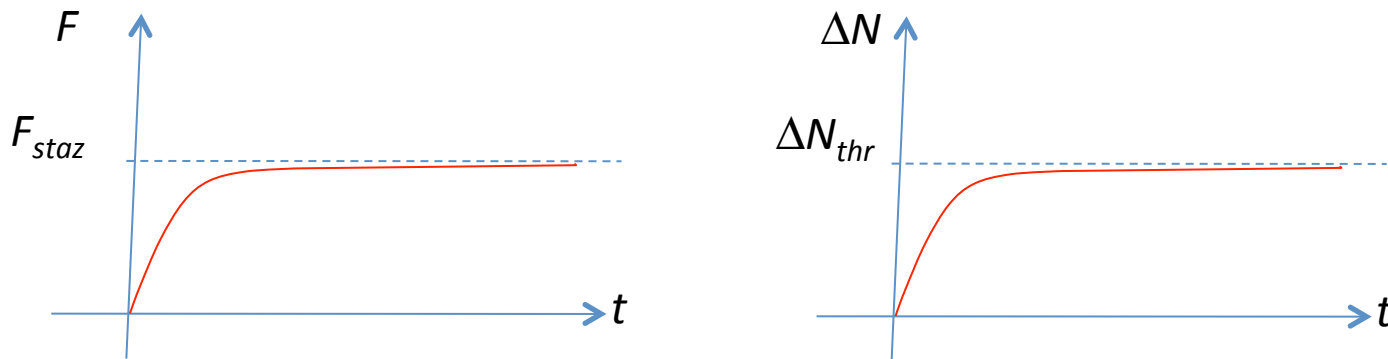
The density of photons gets stationary (constant) when the population is inverted

BEHAVIOR AT THRESHOLD

The presence of a threshold is a well common phenomenon in laser operation
As we have seen, below threshold losses are not compensated by the gain (amplification)

Simplified analysis of the transient leading to stationary conditions:

1. At the beginning there are no photons in the medium $\rightarrow F = 0$ e $\Delta N = \Delta N^0$ (@ $t=0$)
2. In a short time, pumping makes ΔN to get positive
 - $\rightarrow F$ increases up to the stationary state
 - $\rightarrow \Delta N$ increases as well up to the stationary (threshold) value



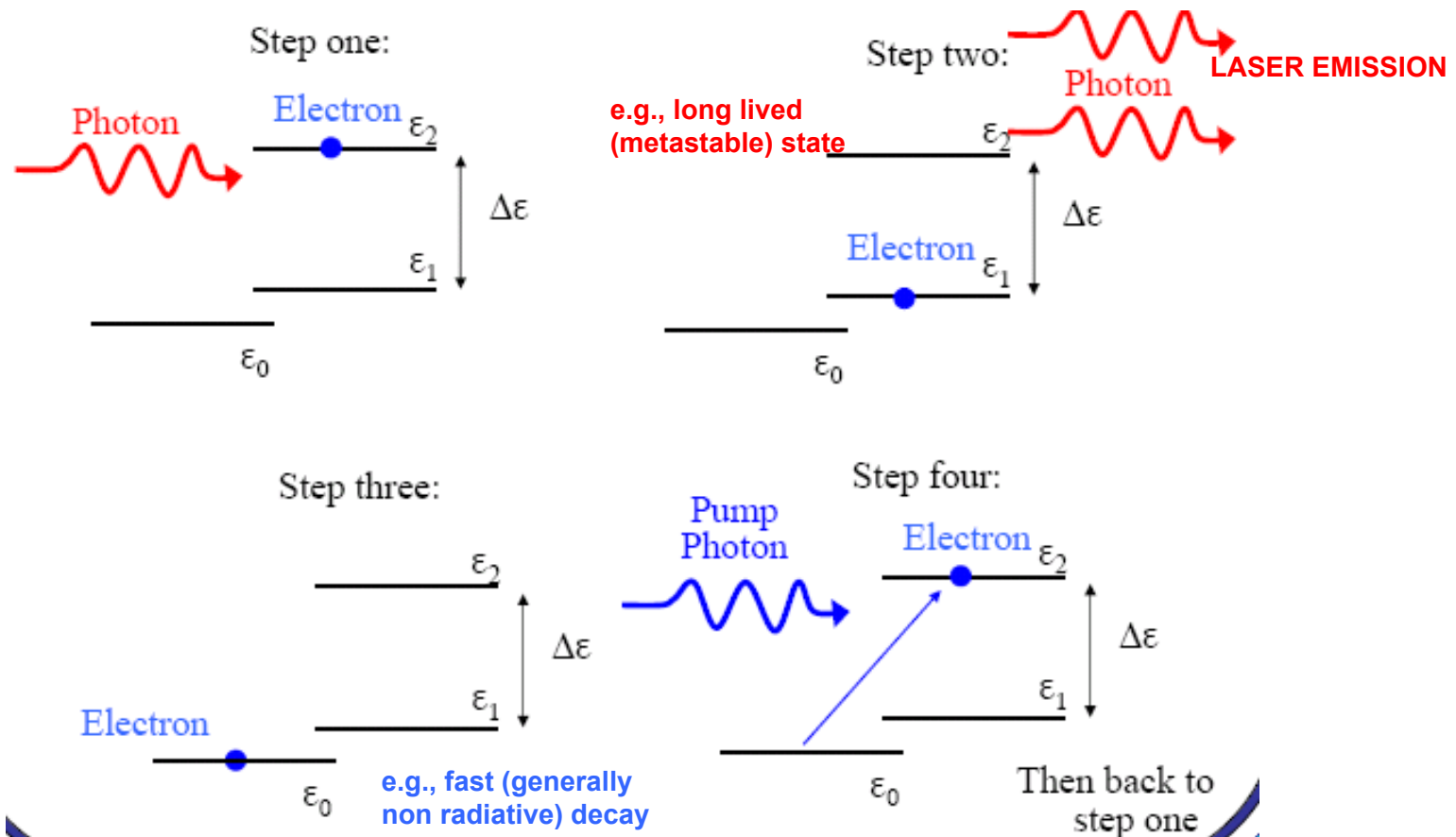
In a very short time (depending on lifetimes and resonator properties, as we will see) stationary conditions are reached (in 1-100 ns, typ.)

MULTILEVEL SYSTEMS

The easiest and usually more effective way to get pumping entails use of resonant radiation
In a two level system such a kind of optical pumping is not feasible (despite of the mathematics above) :

1. in practice, we would need a laser to create a laser (which is, indeed, often the case)
2. more importantly, we will have few chances to distinguish between the pumping radiation and the amplified radiation (the one we expect produced by our laser)

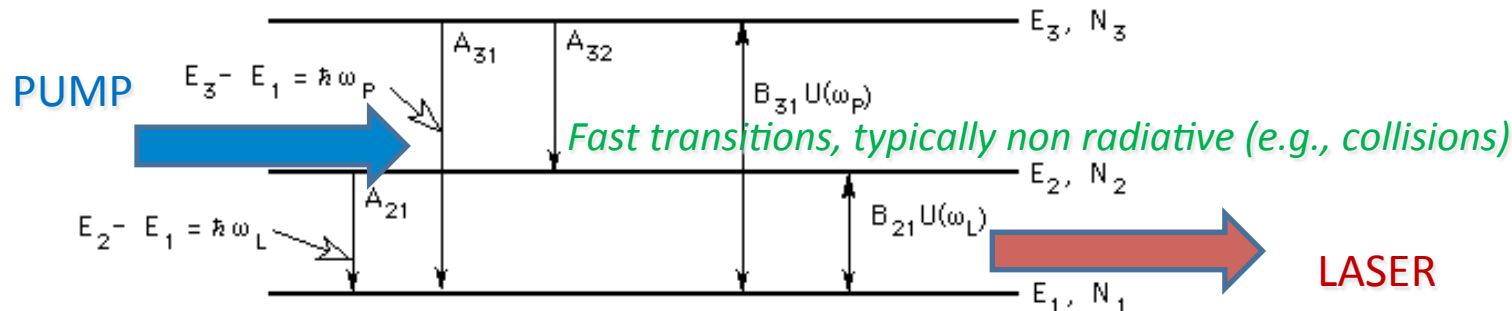
More levels are needed, as, for instance:



OPTICAL PUMPING IN A THREE LEVEL SYSTEM

More than two level are needed in most practical realizations of lasers

EXAMPLE: A "PUMPED" THREE-LEVEL QUANTUM SYSTEM



Key requirement

Optical pump at $\nu_p = (E_3 - E_1)/h \rightarrow$ level E_3 is populated

$\rightarrow$ population is rapidly transferred to E_2

$\rightarrow N_2 > N_1$ (inversion and lasing at $\nu_L = (E_2 - E_1)/h$)

$$A_{32} \gg A_{21}$$

Master rate equations which include "laser" and "pumping" radiation, but in which thermal radiation is neglected:

$$\frac{d}{dt} N_1 = N_3 A_{31} + N_2 A_{21} + (N_3 - N_1) B_{31} U(\omega_p) + (N_2 - N_1) B_{21} U(\omega_L) \quad [\text{V-1a}]$$

Boring mathematics...

$$\frac{d}{dt} N_2 = N_3 A_{32} - N_2 A_{21} - (N_2 - N_1) B_{21} U(\omega_L) \quad [\text{V-1b}]$$

R. Victor Jones, March 14, 2000

$$\frac{d}{dt} N_3 = -N_3 A_{31} - N_3 A_{32} - (N_3 - N_1) B_{31} U(\omega_p) \quad [\text{V-1c}]$$

MASTER EQUATIONS FOR THREE LEVEL SYSTEM I

Of course, only two of these equations are independent, since we assume that there are a fixed number of systems N distributed over these energy levels. In what follows, we define

$$R = U(\omega_p) B_{31} (N_1 - N_3) / N$$

Pumping rate (here denoted as R)

as the **pumping rate** with $N_3 = N - N_1 - N_2$.

We now study the steady state solutions of two independent rate equations -- i.e.

$$\begin{aligned} 0 &= N_3 A_{32} - N_2 A_{21} - (N_2 - N_1) B_{21} U(\omega_L) \\ 0 &= -N_3 (A_{31} + A_{32}) - (N_3 - N_1) B_{31} U(\omega_p) \approx -N_3 (A_{31} + A_{32}) + R N \end{aligned} \quad [V-2a]$$

Steady state solutions

which may be written

$$\begin{aligned} N_1 [A_{32} - B_{21} U(\omega_L)] + N_2 [A_{32} + A_{21} + B_{21} U(\omega_L)] &= N A_{32} \\ N_1 [A_{31} + A_{32}] + N_2 [A_{31} + A_{32}] &= N (A_{31} + A_{32}) - R N \end{aligned} \quad [V-2b]$$

By messy, but trivial algebra, we find

$$\begin{aligned} N_1 &= - \frac{N [R (A_{32} + A_{21} + B_{21} U(\omega_L)) - (A_{31} + A_{32}) (A_{21} + B_{21} U(\omega_L))]}{[A_{31} + A_{32}] [A_{21} + 2B_{21} U(\omega_L)]} \\ N_2 &= \frac{N [R (A_{32} - B_{21} U(\omega_L)) + (A_{31} + A_{32}) B_{21} U(\omega_L)]}{[A_{31} + A_{32}] [A_{21} + 2B_{21} U(\omega_L)]} \end{aligned}$$

Population inversion between levels 2 and 1 @ steady state

Therefore, the all important population difference may be expressed as

$$N_2 - N_1 = \frac{N [R (2A_{32} + A_{21}) - A_{21} (A_{31} + A_{32})]}{[A_{31} + A_{32}] [A_{21} + 2B_{21} U(\omega_L)]} \quad [V-4a]$$

or, with regrouping of terms, as

$$\begin{aligned} N_2 - N_1 &= \frac{N [R (2A_{32} + A_{21}) - A_{21} (A_{31} + A_{32})]}{A_{21} [A_{31} + A_{32}] \left[1 + \frac{2B_{21} U(\omega_L)}{A_{21}} \right]} \\ &= \frac{N [R (2A_{32} + A_{21}) - A_{21} (A_{31} + A_{32})]}{A_{21} [A_{31} + A_{32}] \left[1 + \frac{I(z, \omega_L)}{I_{crit}} \right]} \end{aligned} \quad [V-4b]$$

Note that, since $A_{32} \gg A_{21}$, the condition of inversion of population ($N_2 > N_1$) can be easily reached

where $I_{crit} = (c/n) (A_{21} / 2B_{21})$.

MASTER EQUATIONS FOR THREE LEVEL SYSTEM II

e.m. intensity in the active (pumped) medium

Since the spatial change in the Poynting vector associated with a beam propagating through the laser medium is equal to the rate of energy density lost (or gained) by the beam, **you can show** that

$$\frac{1}{I(z, \omega)} \frac{d}{dz} I(z, \omega) = -(N_1 - N_2) (c/n) (\hbar \omega B_{21}) (F(\omega)/V) \quad [V-5]$$

We'll see more on the "lineshape" in the following

where $F(\omega)$ is the *line shape* function of the $E_2 - E_1$ absorption line. Using Equation [V-4b], we may write

$$\frac{1}{I(z, \omega)} \frac{d}{dz} I(z, \omega) = \frac{R(2A_{32} + A_{21}) - A_{21}(A_{31} + A_{32})}{A_{21}[A_{31} + A_{32}] \left[1 + \frac{I(z, \omega)}{I_{crit}} \right]} \left(\frac{c}{n} \right) \frac{N \hbar \omega B_{21} F(\omega)}{V} \quad [V-6]$$

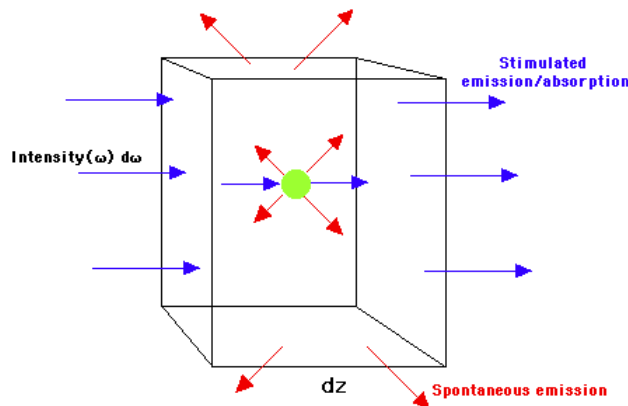
Gain of the active (pumped) medium
(defined as the ratio between the e.m. intensity at the "end" and at the "beginning" of the active medium)

Therefore, we may write

$$\frac{1}{I(z, \omega)} \left[1 + \frac{I(z, \omega)}{I_{crit}} \right] \frac{d}{dz} I(z, \omega) = \mathcal{G} \quad [V-7a]$$

where we identify the *gain of the medium* as

$$\mathcal{G} = \frac{R(2A_{32} + A_{21}) - A_{21}(A_{31} + A_{32})}{A_{21}[A_{31} + A_{32}]} \left(\frac{c}{n} \right) \frac{N \hbar \omega B_{21} F(\omega)}{V} \quad [V-7b]$$



The **gain** $\mathcal{G}$, here introduced for the first time, is an important parameter for laser operation (only at sufficiently large gains the losses are overcome by the additional photon stemming from amplification)

GAIN IN THE THREE LEVEL SYSTEM

Thus, we have an interesting and useful model for the "gain behavior" (growth in intensity with position) of a beam as a function of initial intensity -- viz.

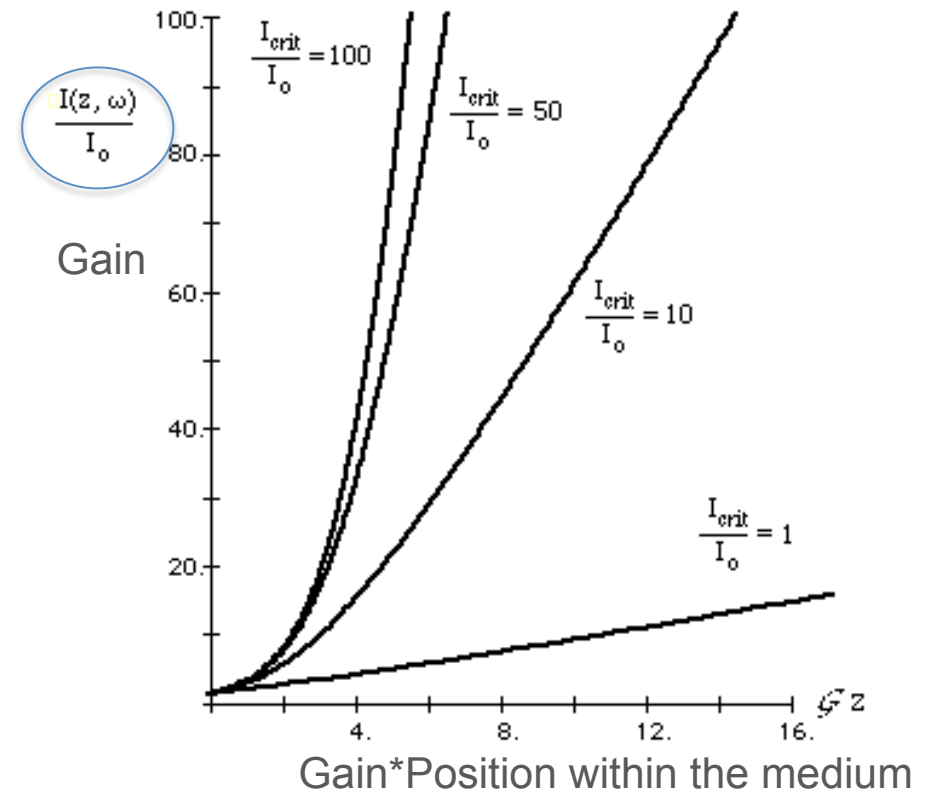
$$\ln\left(\frac{I(z, \omega)}{I_o}\right) + \frac{I(z, \omega) - I_o}{I_{crit}} = G z$$

For $I_o \ll I_{crit}$ $I(z, \omega) = I_o \exp(G z)$ "Inverse Beer's Law"

For $I_o \gg I_{crit}$ $I(z, \omega) = I_o + I_{crit} G z$ Linear regime

With: $I_{crit} = (c/n) (A_{21}/2B_{21})$

The mathematics suggests that, depending on the ratio between I_o (the e.m. intensity "at the beginning" of the active medium) and I_{crit} (similar to the saturation intensity, it's affected by the material properties) different amplification regimes can be achieved



*At relatively low incoming intensity, the gain grows exponentially with the position along the axis of the medium --> **huge gain possible!***

PUMPING MECHANISMS

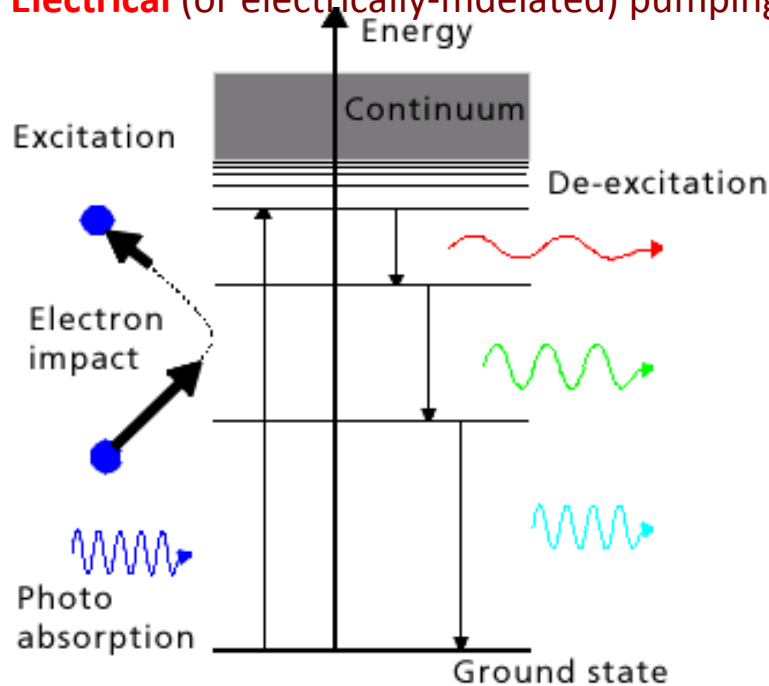
We have seen how, by suitably preparing (**pumping**) a quantum system, it is possible to get amplification, i.e., **gain**

The pumping is typically (not always, though) accomplished by exploiting additional energy levels with respect to those involved in lasing

The pumping can be realized by a variety of methods

Roughly, we can distinguish among:

- **Optical** pumping (photons are used to promote the transition leading to inversion of population)
- **Electrical** (or electrically-mediated) pumping (collisional processes involving electrons are used)



In any case:

External energy must be “injected” into the system in order to achieve inversion of population

The pumping efficiency has to be accounted in the overall efficiency budget (obviously, the transfer of energy has a below unit efficiency; moreover, typically the so produced heat must be removed, that requires energy as well)

CLASSIFICATION OF (PRACTICAL) LASER SYSTEMS

An initial, rough, classification of laser systems can be made according to the physical state of the active medium (the one involved in the amplification, hence in the lasing action)

Solid state lasers:

Ruby, Nd:YAG, rare earth, color centers and other DPSSL (diode-pumped solid state lasers), Ti:Sa, diode lasers (those we will treat specifically!), etc.

Gas lasers:

HeNe, Ar⁺, HeCd, CO₂, metal vapors, etc.

Liquid state lasers:

Dye lasers (liquid solution of dye molecules – existing also in the solid state)

An additional classification, often coincident with the previous one, can be made based on the method used to pump the active medium

We will follow here such an approach in order to start looking at the laser technologies

SOME ACTIVE MEDIA (AND WAVELENGTH)

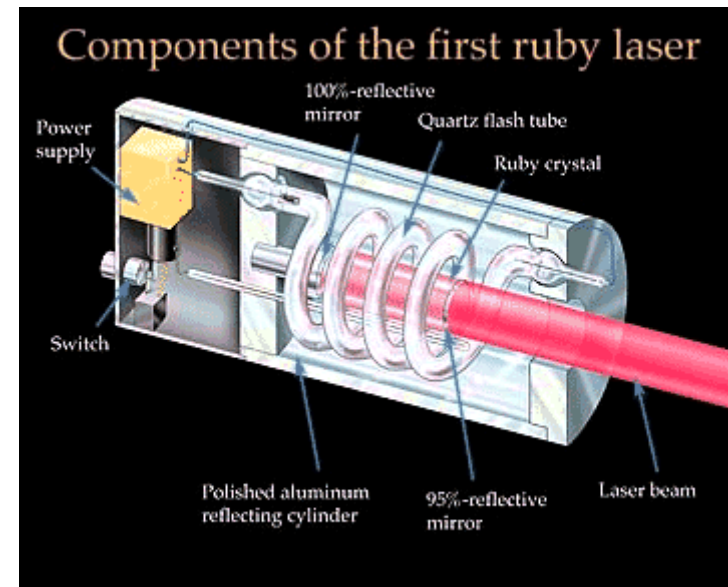
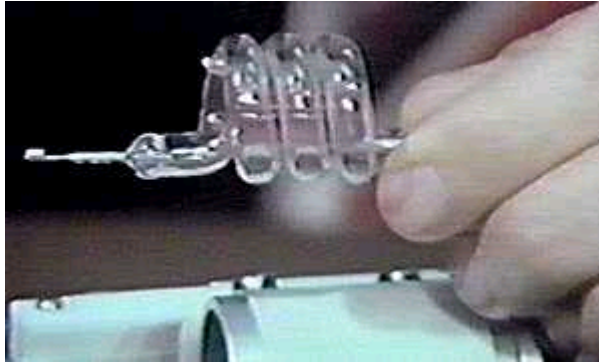
• Neon atoms in a gas (HeNe)	6328 Å
• Chromium atoms in Ruby solid host	6943 Å
• Neodymium atoms in glass/YAG solid host	1.06 μm
• Erbium atoms in glass fiber host	1.5 μm
• Molecular dyes in water or alcohol host	400-1000 nm
• Titanium atoms in a sapphire host	0.7-1.02 μm
• Argon ions in a argon gas	350 – 520 Å n
• CO ₂ gas	10 μm
• Electrons in semiconductors:	
Al _x Ga _{1-x} As	0.7-0.9 μm
In _x Ga _{1-x} As _{1-y} P _y	1.1-1.6 μm
• OH gas molecules	~ 30 cm

ANOTHER LIST ACCORDING TO PUMPING

	Wavelength	Power	Operating mode	Applications	Optical (O) Electronic (E)
Semiconductor diode lasers					
Single diodes	Infrared to visible	1 mW - 100 mW	Continuous and pulsed modes	Optoelectronics	O/E (as we will see more into the details, current produces electron-hole pairs in a semiconductor junction)
Diode laser bars	Infrared to visible	up to 100 W	Continuous and pulsed modes	Pumping light source for solid state lasers	
Solid state lasers					
Nd:YAG laser	1.06 μm	1 W - 3 kW	Continuous and pulsed modes	Materials processing, measurement, medicine	O (lamps, typically flash lamps, or other lasers, called pump lasers)
Rubin-Laser	red	Several MW	Pulsed mode	Measurement, pulse holography	
Gas lasers					
CO ₂ -Laser	10.6 μm	1 W - 40 kW (100 MW in pulsed mode)	Continuous and pulsed modes	Materials processing, medicine, isotope separation	E (electrical discharge + collisions)
Excimer laser	193 nm, 248 nm, 308 nm (and others)	1 kW - 100 MW	gepulster Betrieb, Pulslänge 10 ns - 100 ns	Micro-machining, laser chemistry, medicine	E (electrical discharge + excimer formation)
HeNe laser	632.8 nm (most prominent)	1 mW - 1 W	kontinuierlicher Betrieb	Measurement, holography	
Argon ion laser	515 458 nm (several)	1 mW - 150 W	Continuous and pulsed modes	Printing technology, pumping laser for dye laser stimulation, medicine	E (electrical discharge + collisions)
Dye laser	Continuous between infrared and ultraviolet (different dyes)	1 mW - 1 W	Continuous and pulsed modes	Measurement, spectroscopy, medicine	O (pump lasers or more seldom lamps)

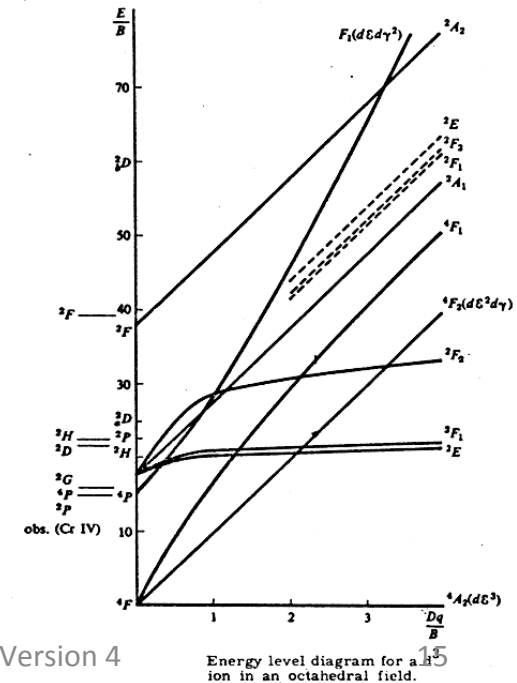
RUBY LASER I

First practical laser (pulsed): Maiman, 1960



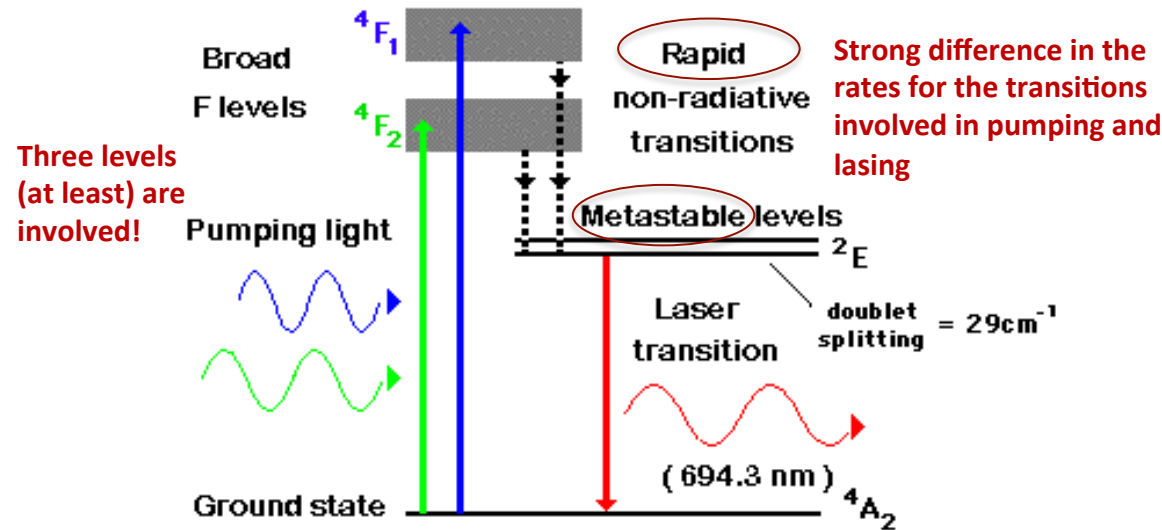
Il rubino è un cristallo di allumina (sesquiossido di alluminio: Al_2O_3), drogato con circa lo 0.05% di ioni cromo trivalente Cr^{3+} , che gli conferiscono il caratteristico color rosso. L'alluminio e l'ossigeno sono otticamente inerti, mentre gli ioni Cr^{3+} sono i centri otticamente attivi.

Il laser a rubino è un sistema a tre livelli ed è meno efficiente di uno a quattro, come ad esempio il laser al Neodimio, che lo ha rimpiazzato nella maggior parte delle applicazioni. Il materiale attivo nel laser a rubino è una barretta di zaffiro sintetico drogato con circa lo 0.01%-0.5% di cromo. Questo drogaggio corrisponde a circa 10^{19} atomi di cromo per centimetro cubo. La luce emessa dagli atomi di cromo colora di rosso o rosa il cristallo. Il materiale è facile da trovare e le barrette di 3-25 mm di diametro sono disponibili a partire da lunghezze di 20 cm. Il rubino resiste bene al danneggiamento ottico e conduce il calore meglio del vetro. La struttura dei livelli energetici nel rubino è mostrata nella Figura 3.1.2. La luce visibile in una delle due bande di pompaggio porta gli ioni cromo³⁺ in una delle due bande eccitate da cui decadono in circa 100 ns a due livelli metastabili con tempo di vita medio a temperatura ambiente di 3 ms. L'emissione è permessa da entrambi i livelli, ma la transizione dal livello E è predominante. Il livello fondamentale è il livello inferiore della transizione laser e questo vuol dire che è necessaria una pompa ad alta potenza per portare la metà degli atomi più uno ai livelli più alti di energia e quindi avere un'inversione di popolazione. Questo innalza la soglia del laser e comporta una bassa efficienza.



RUBY LASER II

Discrete levels of Cr^{3+} in Al_2O_3 matrix



Energy levels of chromium ions in ruby

L'eccesso di energia rimane nel laser sotto forma di calore limitando il ritmo di ripetizione a pochi Hertz eccetto che per barre molto piccole, per cui è necessario un sistema di refrigerazione. Il tempo di vita di 3ms del livello energetico più alto da al laser a rubino la capacità di immagazzinare molta più energia di quella immagazzinata dal laser al Neodimio con una barretta delle stesse dimensioni e genera impulsi di energia più elevata. Il basso ciclo di lavoro, però, è un serio limite alla potenza media del laser.

Caratteristiche del fascio

L'oscillatore laser a rubino può produrre impulsi di qualche millisecondo da 50 a 100 Joule. Nella configurazione amplificata può emettere più di 100 Joule. La durata degli impulsi dipende dalla lunghezza degli impulsi della lampada di pompaggio e va da frazioni a poche unità di millisecondo. La potenza media dell'impulso non supera le decine di KW. Il basso tasso di ripetizione limita la potenza media di un oscillatore a barretta singola attorno ai 100 W.

L'instabilità nei processi di emissione e di assorbimento causa delle brusche oscillazioni negli impulsi di lunga durata cosicché la potenza istantanea varia considerevolmente. Per ovviare a ciò si usa il Q-switching. Questo processo limita l'energia degli impulsi in un singolo oscillatore a qualche Joule, comprimendo però la durata dell'impulso a 10-35 ns. In questo modo si possono raggiungere picchi di potenza di 100 MW. Per oscillatori amplificati si possono avere picchi di 1 GW ed energie di più di 10 Joule per impulso.

Key point (typical for solid-state lasers):

The impurity (Cr, in this case) behaves almost like an isolated atom, or, better, trivalent ion

Optical pumping with flash lamps

Typical pulses up to 100 ms duration and average power up to several W

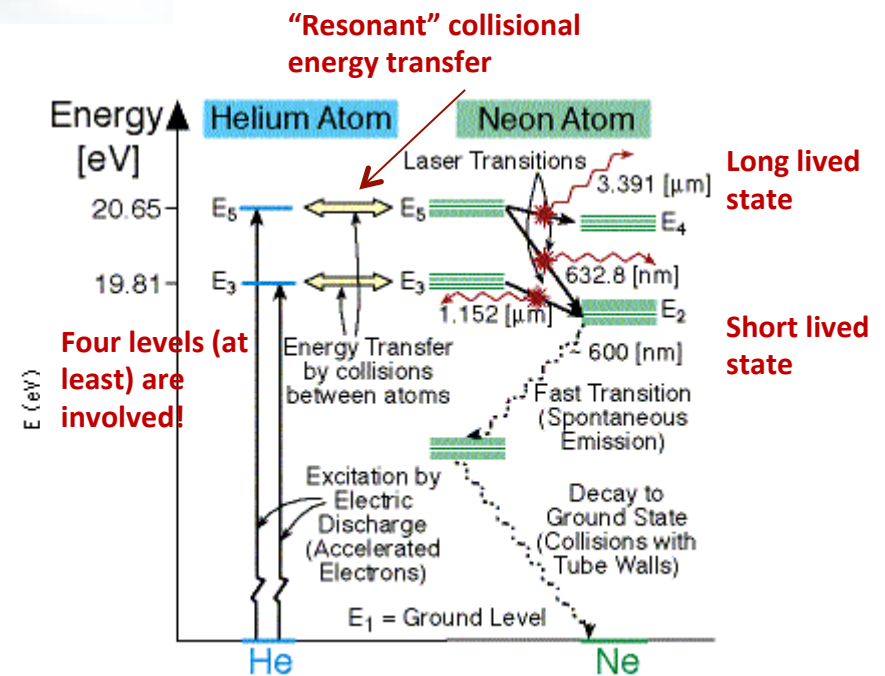
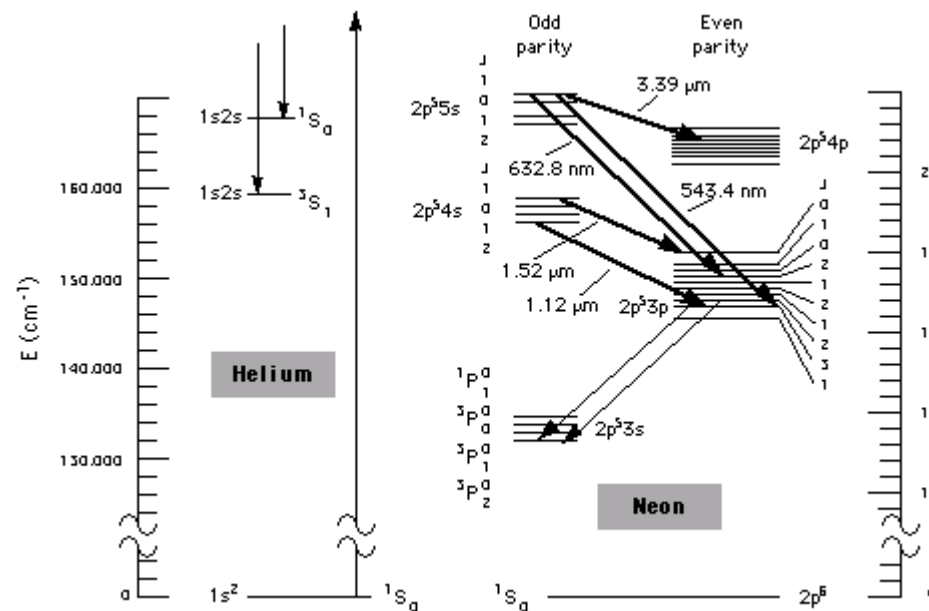
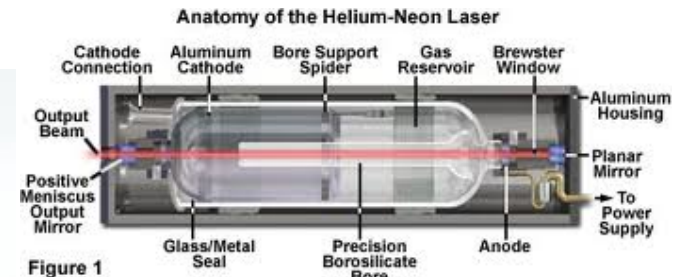
Main limitation (due to thermal effects): poor repetition frequency

Presently, few (or no) Ruby lasers are produced and few applications (e.g., tattoo removal or other dermatological)

HeNe LASER I

First continuous wave (CW) laser (1962)

Low power (< 100 mW), excellent stability and optical properties: still widely used in metrology



The Mechanism: A dc or rf electrical discharge is established in a gas mixture of helium (~ 90%) and neon (~10%). The helium atoms are excited to long-lived metastable states by a variety of processes involving energetic electron impact. The excitation energy of the helium metastables is transferred to neon atoms by resonance scattering to yield laser-active neon metastables.

HeNe LASER II

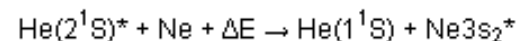
Il mezzo di amplificazione del laser, come suggerisce il nome, è una miscela di gas **elio** e **neon** in proporzioni che vanno da 5:1 a 20:1, contenuti in un tubo di vetro a una pressione variabile a seconda della grandezza del tubo stesso, grosso modo pari a 50 **Pa** per centimetro di lunghezza del risuonatore [2]) contenuto nel tubo di vetro.

L'energia della fonte di pompaggio del laser deriva da una scarica elettrica di circa 1000**V** fra un **anodo** e un **catodo** posti agli estremi del tubo di vetro, e con correnti variabili da 5 a 100 milliampere nel funzionamento normale ad onda continua. [3].

La cavità ottica del laser è costituita di solito da uno **specchio** altamente riflettente a una estremità e di un accoppiatore (specchio semiriflettente) all'altra estremità, con una trasmissività verso l'esterno dell'1% circa. I laser a elio-neon sono in genere piccoli, con tubi laser da 15 a 50 cm e potenze ottiche in uscita da 1 a 100 milliwatt. **Rather small current and voltage needed for the discharge to be efficient**

Il fenomeno laser inizia in questo tipo di dispositivo con la collisione degli elettroni con gli atomi di elio: questi eccitano l'elio e lo portano dallo **stato fondamentale** agli stati eccitati 2^3S_1 e 2^1S_0 , **metastabili** e a lunga vita. Gli atomi eccitati di elio collidono poi con quelli di neon cedendo loro l'energia ricevuta e portando gli elettroni del neon nello stato $3s_2$ [3]. Questo a causa di una coincidenza dei **livelli energetici** fra gli atomi di elio e quelli di neon.

Questo processo è sintetizzato nella seguente equazione di reazione:



dove (*) rappresenta uno stato eccitato e ΔE è la piccola differenza di energia fra gli stati energetici dei due atomi, dell'ordine di 0.05 **eV** o 387 cm^{-1} , che è fornita dall'energia cinetica. [3].

Rather complex pumping mechanism:

Discharge $\rightarrow$ electron collisions $\rightarrow$ He* $\rightarrow$ Ne*

Rather efficient, yet (10W of electrical power $\rightarrow$ 10 mW of laser output)

HeNe LASER III

Il numero di atomi di neon che entra in stato di eccitazione cresce con il procedere delle collisioni con gli atomi di elio, causando alla fine una **inversione di popolazione**; l'emissione spontanea e stimolata dalle transizioni fra gli stati $3s_2$ e $2p_4$ causa alla fine l'emissione di luce laser della canonica lunghezza d'onda di 632.82 nm. Dopodiché, avviene un rapido decadimento dallo stato $2p$ allo stato fondamentale $1s$: poiché il livello superiore del neon satura con correnti più alte e quello inferiore varia linearmente con la corrente, i laser HeNe sono costretti a generare potenze molto piccole pena la perdita dell'inversione di popolazione.^[3]

Con una appropriata scelta degli specchi della cavità è possibile far funzionare i laser HeNe anche su frequenza diverse da quella classica: esistono infatti transizioni fra stati anche nell'**infrarosso**, a lunghezze d'onda di 3.39 μm e 1.15 μm , ed una varietà di transizioni nello spettro visibile, comprese **verde** (543.5 nm, il cosiddetto laser GreeNe), una **gialla** (594 nm) e una **arancione** (612 nm). La normale lunghezza d'onda rossa a 633 nm ha un guadagno minore delle altre, soprattutto delle linee a 1.15 μm and 3.39 μm lines, ma queste si possono sopprimere usando degli specchi rivestiti apposta per non riflettere luce di quella lunghezza d'onda.

La banda di guadagno del laser HeNe è dominata dall'**allargamento Doppler**, ed è molto stretta: circa 1.5 GHz per la transizione laser a 633nm^{[6][7]} su un singolo **modo longitudinale**. La visibilità del fascio laser e le sue eccellenti qualità di coerenza spaziale lo rendono una sorgente molto utile per **olografia** e come luce di riferimento per la **spettroscopia**. È anche uno dei sistemi di test per la definizione del metro campione^[8].

Particularly strong emissions

$1s^2 2s^2 2p^5 5s:$	$^1P_1 \rightarrow$	$1s^2 2s^2 2p^5 3p:$	3S_1	$l_{\text{vacuo}} = 0.5435 \text{ mm};$	$l_{\text{air}} = 0.5433 \text{ mm}$
$1s^2 2s^2 2p^5 5s:$	$^1P_1 \rightarrow$	$1s^2 2s^2 2p^5 3p:$	3P_2	$l_{\text{vacuo}} = 0.6330 \text{ mm};$	$l_{\text{air}} = 0.6328 \text{ mm}$
$1s^2 2s^2 2p^5 4s:$	$^1P_1 \rightarrow$	$1s^2 2s^2 2p^5 3p:$	3P_2	$l_{\text{vacuo}} = 1.1526 \text{ mm};$	$l_{\text{air}} = 1.1523 \text{ mm}$
$1s^2 2s^2 2p^5 4s:$	$^1P_1 \rightarrow$	$1s^2 2s^2 2p^5 3p:$	1S_0	$l_{\text{vacuo}} = 1.5235 \text{ mm};$	$l_{\text{air}} = 1.5231 \text{ mm}$
$1s^2 2s^2 2p^5 5s:$	$^1P_1 \rightarrow$	$1s^2 2s^2 2p^5 4p:$	3P_2	$l_{\text{vacuo}} = 3.3922 \text{ mm};$	$l_{\text{air}} = 3.3913 \text{ mm}$

Good optical properties
(related also on good
optical cavity, we'll see
more)

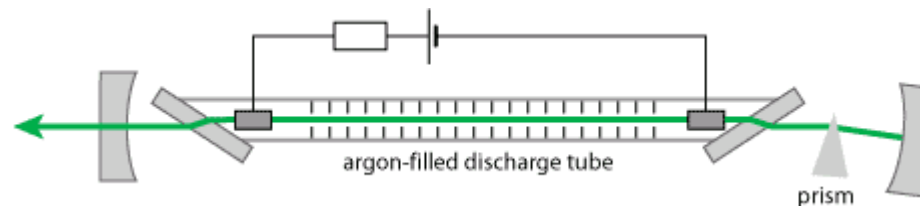
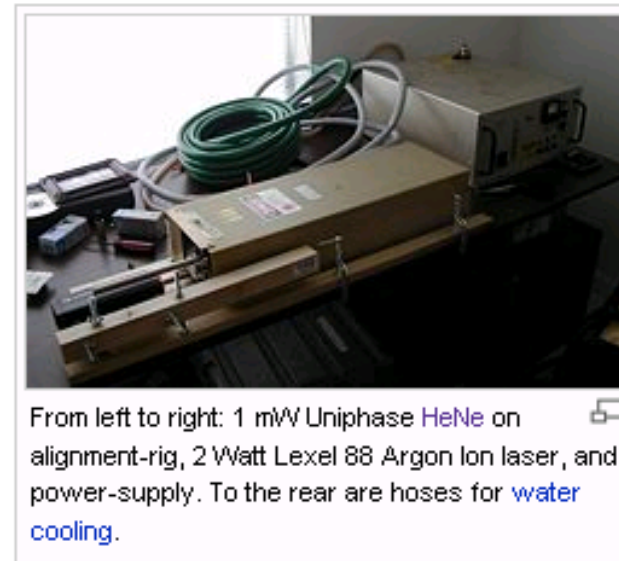
Different wavelengths can
be emitted, from green to
near-infrared

LASER Ar⁺ I

Active medium: **ions** produced and excited in an electron discharge

→ very bad overall efficiency, but relatively high power (tens of W) and remarkable optical properties

An **ion laser** is a **gas laser** which uses an **ionized** gas as its lasing medium.^[1] Like other gas lasers, ion lasers feature a sealed cavity containing the laser medium and mirrors forming a **Fabry-Perot** resonator. Unlike **HeNe** lasers, the energy level transitions that contribute to laser action come from **ions**. Because of the large amount of energy required to excite the ionic transitions used in ion lasers, the required current is much greater, and as a result all but the smallest ion lasers are **water cooled**. A small air cooled ion laser might produce, for example, 130mW of light with a tube current of 10A @ 105V. This is a total power draw over 1 kW, which translates into a large amount of heat which must be dissipated.



1 kW total electric consumption for obtaining 130 mW laser power (and this does not include water cooling and related chillers!)

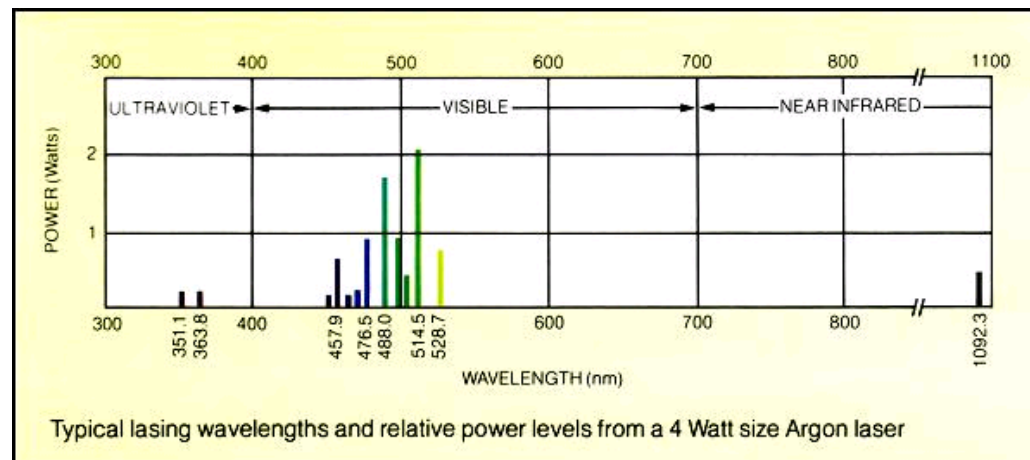
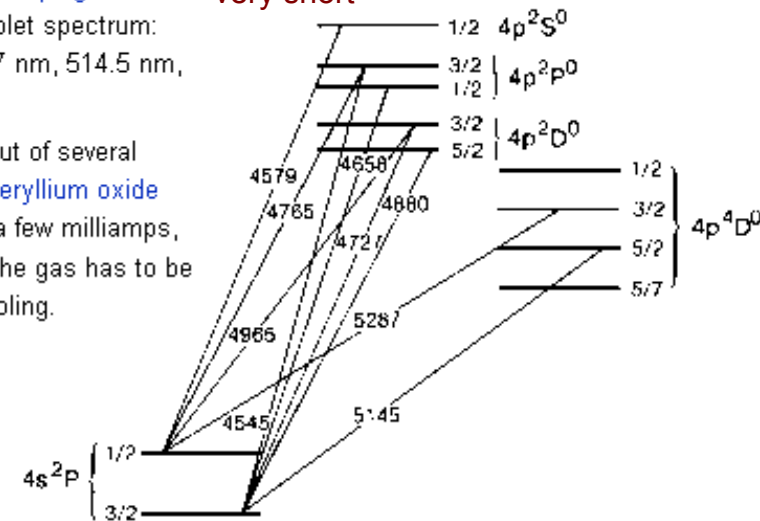
LASER Ar⁺ II

The Argon laser was invented in 1964 by William Bridges at Hughes Aircraft and is one of a family of ion lasers that use a noble gas as the active medium.

Argon lasers are used for [retinal phototherapy](#) (for [diabetes](#)), [lithography](#), and [pumping](#) other lasers. Argon lasers emit at several wavelengths through the visible and ultraviolet spectrum: 351 nm, 454.6 nm, 457.9 nm, 465.8 nm, 476.5 nm, 488.0 nm, 496.5 nm, 501.7 nm, 514.5 nm, 528.7 nm.

Common argon and krypton lasers are capable of emitting continual wave output of several milliwatts to tens of watts continually. Their tubes are usually made of [kovar](#), [beryllium oxide ceramics](#), or [copper](#). In comparison with the [helium-neon lasers](#) requiring just a few milliamps, the current used for pumping the krypton laser ranges in several amperes, as the gas has to be ionized. The ion laser tube produces a lot of waste heat and requires active cooling.

The processes induced by the discharge (rapidly) populates all such excited states, whose lifetime is not very short



Different laser lines can be produced, either selected or used together (multiline operation) to increase the power

Still many applications (e.g., metrology, biomedics, pump for other lasers, etc.)

A VERY FEW WORDS ON MOLECULES

The **Lennard-Jones potential** (also referred to as the **L-J potential**, **6-12 potential**, or **12-6 potential**) is a mathematically simple model that approximates the interaction between a pair of neutral atoms or molecules. A form of the potential was first proposed in 1924 by [John Lennard-Jones](#).^[1] The most common expressions of the L-J potential are

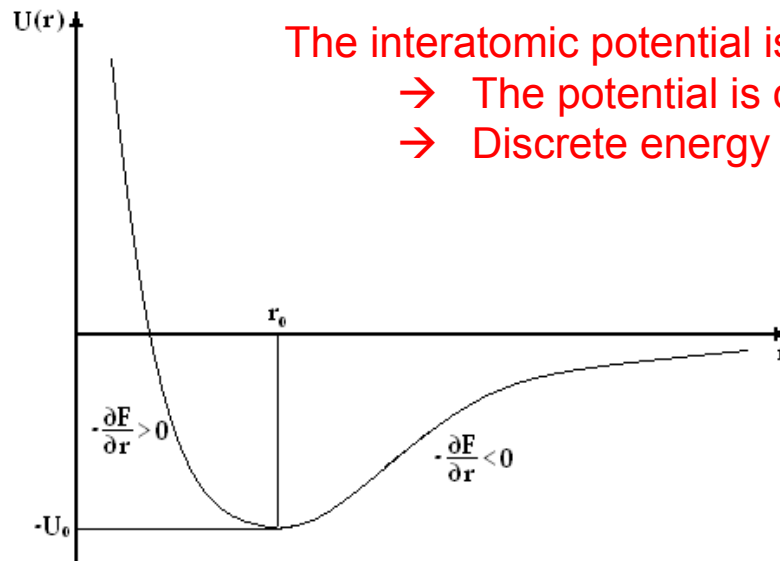
$$V_{LJ} = 4\varepsilon \left[\left(\frac{\sigma}{r} \right)^{12} - \left(\frac{\sigma}{r} \right)^6 \right]$$

$$= \varepsilon \left[\left(\frac{r_m}{r} \right)^{12} - 2 \left(\frac{r_m}{r} \right)^6 \right]$$

where ε is the depth of the **potential well**, σ is the finite distance at which the inter-particle potential is zero, r is the distance between the particles, and r_m is the distance at which the potential reaches its minimum. At r_m , the potential function has the value $-\varepsilon$. The distances are related as $r_m = 2^{1/6}\sigma$. These parameters can be **fitted** to reproduce experimental data or accurate **quantum chemistry** calculations. Due to its computational simplicity, the Lennard-Jones

It is possible to describe the potential felt by two (or more, in small number) atoms placed at short relative distance r by a potential such as the Lennard-Jones one

The interaction force (i.e., the spatial derivative of the potential!) is repulsive for $r \rightarrow 0$ and attractive for large r



The interatomic potential is “quantum-well”-like

- The potential is confining
- Discrete energy levels exist

Note: such molecular energy levels are not (necessarily) associated with electronic transitions. They can in fact be associated with interatomic motion (rotational and vibrational modes such as, bending, stretching, and so on). The corresponding energy spectrum typically involves relatively small energies $\rightarrow$ infrared photons!

CO₂ (CO) LASER I

I laser molecolari

Vi sono diversi tipi di laser basati su transizioni tra livelli energetici elettronici, vibrazionali o rotazionali di molecole. Le transizioni rotovibrazionali dello stato elettronico fondamentale hanno lunghezze d'onda nel medio fino al lontano IR (2.5 – 300 μm). La ridotta energia dei livelli energetici coinvolti in queste transizioni porta a un elevato valore del rendimento quantico e a un efficiente meccanismo di eccitazione: tutto ciò produce un rendimento complessivo per questi laser assai alto. Si ottengono, infatti, potenze laser continue di molti kW e energie per impulsi di centinaia di J.

Il laser molecolare più diffuso è quello ad anidride carbonica, CO₂, che oscilla a 10.6 μm e a altre lunghezze d'onda nella regione 9-11 μm ; altri esempi sono il laser a CO a 5 - 6.5 μm e il laser chimico a HF con emissione a 2.7 - 3.3 μm . Quando fu scoperto (1964) il laser a CO₂ erogava poca potenza. Poi ci si accorse che, aggiungendo azoto, si aveva un incremento di potenza, che risultava ancora maggiore con l'aggiunta di elio.

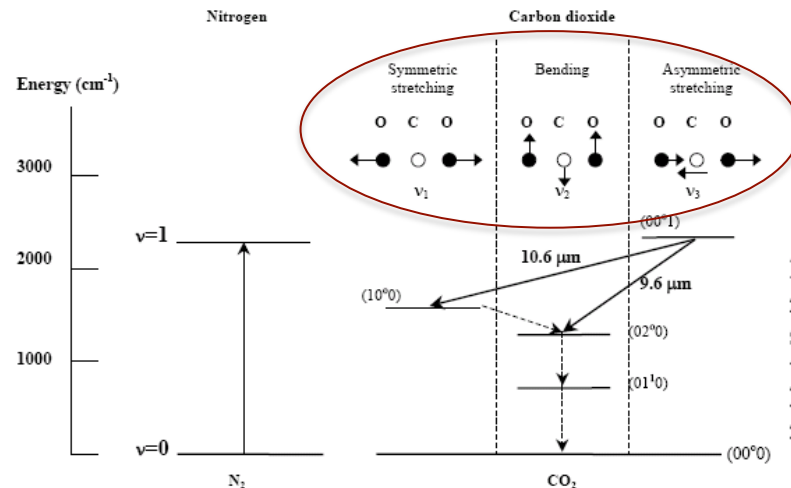


Figura 2.4.1 Modi vibrazionali del CO₂; livelli vibrazionali più bassi e transizioni laser; trasferimento di energia dal N₂

Si intuisce quindi che:

- se la scarica degenera in un arco, che equivale, come resistenza, a un corto circuito e quindi non sostiene un campo elettrico, gli elettroni non acquistano energia sufficiente per l'eccitazione delle molecole del gas.
- esiste un valore ottimale del rapporto (alcune decine di KV/cm atmosfera), quello che corrisponde al valore ottimale dell'energia che gli elettroni devono avere per eccitare i livelli coinvolti.

Il maggior problema di questo e degli altri laser a gas di potenza è proprio quello del raffreddamento della scarica per evitare la formazione di archi anche solo localizzati.

Si usano elettrodi conformati in modo opportuno per evitare scariche. L'impiego di elettrodi a rete consente di far fluire il gas in direzione trasversa rispetto all'asse ottico.

Laser a.a. 2012/13 – <http://www.df.unipi.it/~fuso/dida> - Part 5 - Version 4

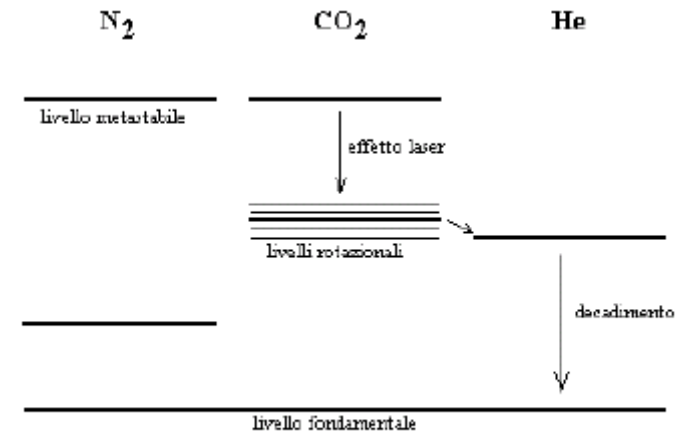


Figura 2.4.2 Livelli energetici del laser a CO₂

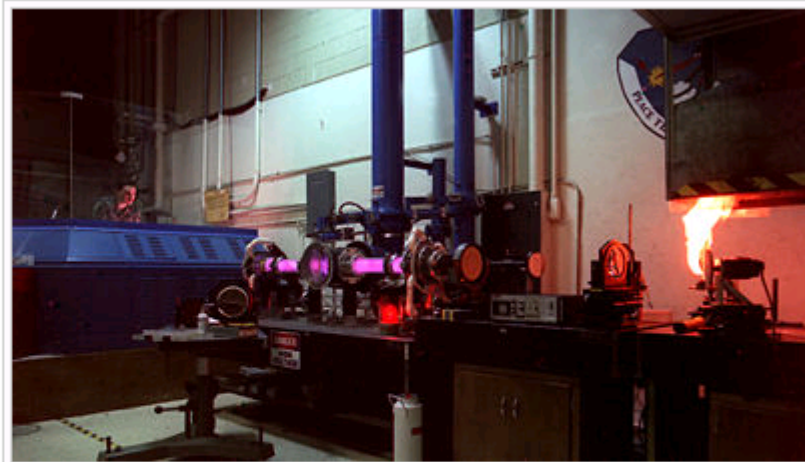
In an electric discharge in a mixture of CO₂, N₂ and He excitation to the upper 00¹ laser level is achieved by electron impact or resonant transfer from vibrationally excited ($v = 1$) N₂ molecules. The N₂ ($v = 1$) level is efficiently excited in the discharge and is a long lived metastable state. The role of He in the gas mixture is to de-activate the lower laser level, to control the electron temperature in the discharge, to stabilize the plasma and to cool the CO₂ molecules by conducting heat to the walls of the discharge tube. Anche la redistribuzione di popolazione tra i livelli rotazionali (termalizzazione dei livelli) contribuisce a svuotare il livello inferiore della transizione.



CO₂ (CO) LASER II

The **carbon dioxide laser** (CO₂ laser)

was one of the earliest **gas lasers** to be developed (invented by **Kumar Patel** of Bell Labs in 1964^[1]), and is still one of the most useful. Carbon dioxide lasers are the highest-power continuous wave **lasers** that are currently available. They are also quite efficient: the ratio of output power to pump power can be as large as 20%.



A test target is vaporized and bursts into flame upon irradiation by a high power continuous wave **carbon dioxide laser** emitting tens of kilowatts of **infrared** light.

The CO₂ laser is still an unsurpassed tool for material processing (e.g., steel cutting and soldering and many others)

This is due to the high power and to the infrared radiation, which does not promote “bond-breaking” or other “chemical-like” processes thus leading to extremely large and relatively localized material heating

The **active laser medium** (laser gain/amplification medium) is a **gas discharge** which is air cooled (water cooled in higher power applications). The filling gas within the discharge tube consists primarily of:

- **Carbon dioxide** (CO₂) (around 10–20 %)
- **Nitrogen** (N₂) (around 10–20%)
- **Hydrogen** (H₂) and/or **xenon** (Xe) (a few percent; usually only used in a sealed tube.)
- **Helium** (He) (The remainder of the gas mixture)

The specific proportions vary according to the particular laser.

The **population inversion** in the laser is achieved by the following sequence:

1. **Electron** impact excites vibrational motion of the nitrogen. Because nitrogen is a **homonuclear molecule**, it cannot lose this energy by **photon** emission, and its excited vibrational levels are therefore **metastable** and live for a long time.
2. Collisional energy transfer between the nitrogen and the carbon dioxide molecule causes vibrational excitation of the carbon dioxide, with sufficient efficiency to lead to the desired population inversion necessary for laser operation.

The CO₂ laser can be constructed to have CW powers between **milliwatts** (mW) and hundreds of **kilowatts** (kW).^[2] It is also very easy to actively **Q-switch** a CO₂ laser by means of a rotating mirror or an electro-optic switch, giving rise to Q-switched peak powers up to **gigawatts** (GW) of peak power.^[3]

Because the laser transitions are actually on vibration-rotation bands of a linear triatomic molecule, the rotational structure of the P and R bands can be selected by a tuning element in the **laser cavity**. Because transmissive materials in the infrared are rather lossy, the **frequency** tuning element is almost always a **diffraction grating**. By rotating the diffraction grating, a particular rotational line of the vibrational transition can be selected. The finest frequency selection may also be obtained through the use of an **etalon**. In practice, together with **isotopic substitution**, this means that a continuous comb of frequencies separated by around 1 cm⁻¹ (30 GHz) can be used that extend from 880 to 1090 cm⁻¹. Such “line-tuneable” carbon dioxide lasers are principally of interest in research applications.

Nd-YAG LASER I

Nd:YAG laser is the most popular of a large array of lasers using rare earth dopants embedded in a matrix

Rare Earth Ion Solid State Lasers:

Neutral atom electronic configurations:

noble gas core xenon: $[Xe] = 1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^6$

rare earth atoms: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 4f^n 5s^2 5p^6 6s^2 = [Xe] 4f^n 6s^2$

Trivalent ion electronic configurations of common laserable rare earth ions:

praseodymium (Pr³⁺): $= [Xe] 4f^2$ Ground state: $3H_4$

neodymium (Nd³⁺): $= [Xe] 4f^3$ Ground state: $4I_{9/2}$

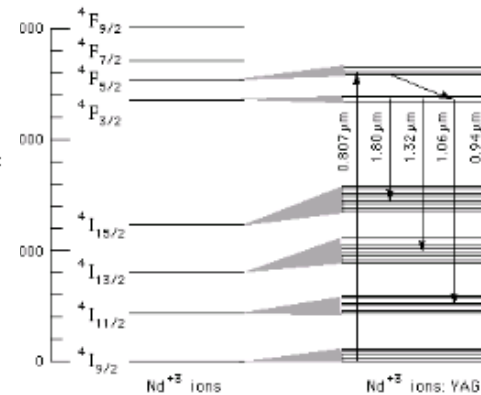
europium (Eu³⁺): $= [Xe] 4f^6$ Ground state:

holmium (Ho³⁺): $= [Xe] 4f^{10}$ Ground state:

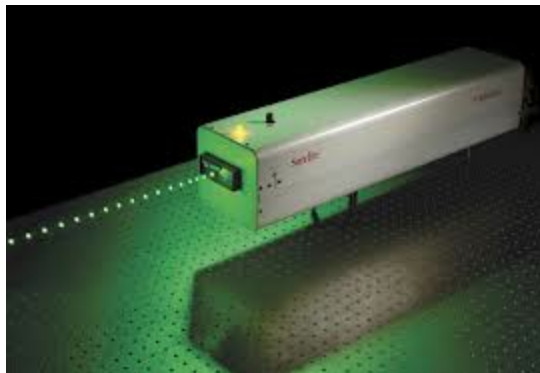
erbium (Er³⁺): $= [Xe] 4f^{11}$ Ground state: $4I_{15/2}$

thulium (Tm³⁺): $= [Xe] 4f^{12}$ Ground state: $3H_6$

ytterbium (Yb³⁺): $= [Xe] 4f^{13}$



The embedding makes available discrete levels (of the 3+ ions) similar to those of an isolated atom (ion), but for a shift and a small broadening



In the original (and still very popular) configuration, the optical pumping is achieved by flash lamps (pumped, typical 10 ps – 100 ns)

Since a few years, diode-pumped (typically, CW) lasers, so called DPSSL, are available with very good power and efficiency

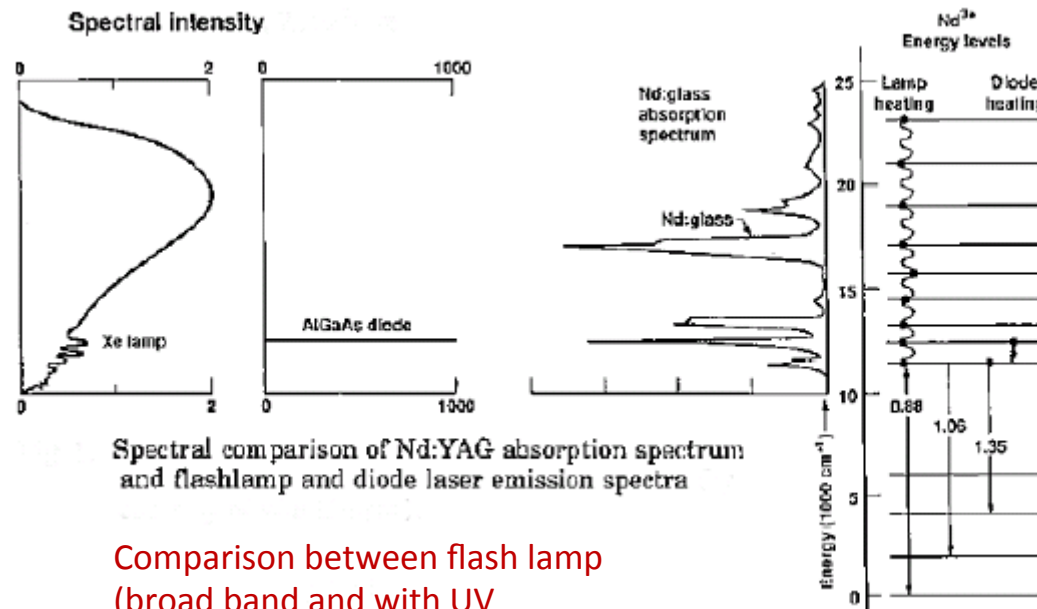
Thanks to the large available power, Nd:YAG can be coupled to nonlinear crystals to generate *higher harmonics* (example: II harm @ 532 nm, III harm @ 354 nm, etc.)

In rare earth atoms (ions), the outer electrons shield the core with respect to the matrix (crystal) field
 → Embedded atoms (ions) behave not too much differently as isolated atoms, while being in the solid-state

Nd-YAG LASER II

Si tratta di uno dei più diffusi laser a stato solido. Il mezzo attivo è costituito da un cristallo di $\text{Y}_3\text{Al}_5\text{O}_{12}$, detto comunemente YAG, drogato con Neodimio (Nd^{3+} che sostituisce Y^{3+}). Costituisce un sistema a 4 livelli che emette a $1.06 \mu\text{m}$ (vicino infrarosso) con pompaggio ottico tramite lampada a Krypton. Il cristallo ha una ottima conduttività termica, il che gli permette di operare senza problemi in continua o ad alte frequenze di ripetizione. Esiste una variante più economica di questo laser, che è il Nd:vetro, dove i centri attivi di neodimio sono ospitati invece che in un cristallo di YAG in un vetro. E' più economico, ma ha una peggiore conducibilità termica, per cui viene utilizzato solo in regime impulsato a basse frequenze di ripetizione.

Il cristallo di Nd:YAG è materiale ideale per un laser a 4 livelli. La vita media del livello laser superiore è relativamente lunga ($250 \mu\text{s}$) e la transizione laser a $1.064 \mu\text{m}$ termina a circa 2000 cm^{-1} al disopra dello stato fondamentale, per cui la popolazione termica del livello laser inferiore a 300 K è inferiore a 10^{-4} e può essere trascurata. Il pompaggio a 809 nm può essere efficacemente ottenuto con un laser a diodo AlGaAs di alta potenza.



Spectral comparison of Nd:YAG absorption spectrum and flashlamp and diode laser emission spectra

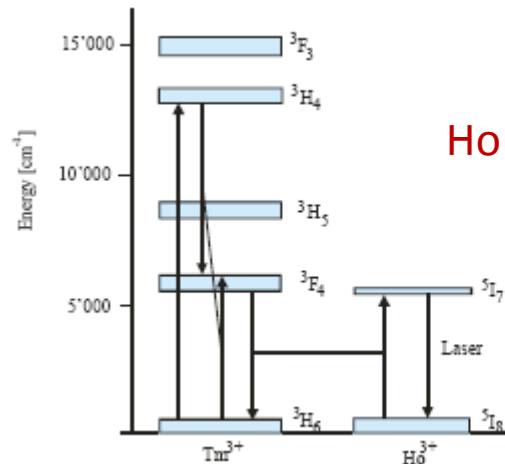
Comparison between flash lamp (broad band and with UV components) and laser diode (@808 nm) optical pumping

Very many applications are typical with Nd:YAG lasers (and relatives)

In pulsed mode (flash lamp pumped) they are used in material processing and in many biomedical applications (dermo, surgery, etc.)

In CW operation (diode laser pumped) they are very useful in metrology (interference, holography, etc), as well in telecommunications, low-end biomedical, replacement for Ar⁺ lasers, pumping other lasers, and even pointers (yes, the green one are typically made with Nd:YAG diode pumped lasers...)

OTHER RUBY'S SONS (SIMILAR TO Nd:YAG)



Ho

Figura 3.3.1: Energy level scheme of Ho^{3+} :YAG co-doped with Tm^{3+} . Pumping with a wavelength of about 785 nm leads to excitation of the Tm^{3+} $^3\text{H}_4$ level. Excited Tm^{3+} $^3\text{H}_4$ and ground state $^3\text{H}_6$ ions can exchange energy leading to a two fold population of $^3\text{F}_4$. From there a second energy transfer excites the Ho^{3+} upper laser level.

Nei cristalli drogati con gli ioni dei metalli di transizione si verificano forti interazioni tra gli stati elettronici e le vibrazioni reticolari (fononi). Queste interazioni elettronico-vibrazionali (*vibroniche*) producono un notevole allargamento omogeneo dei livelli elettronici, rendendoli bande continue. Similmente ai laser a coloranti, i laser vibronici offrono emissione laser a lunghezza d'onda accordabile e un'ampiezza di banda tale da poter generare impulsi ultra-brevi.

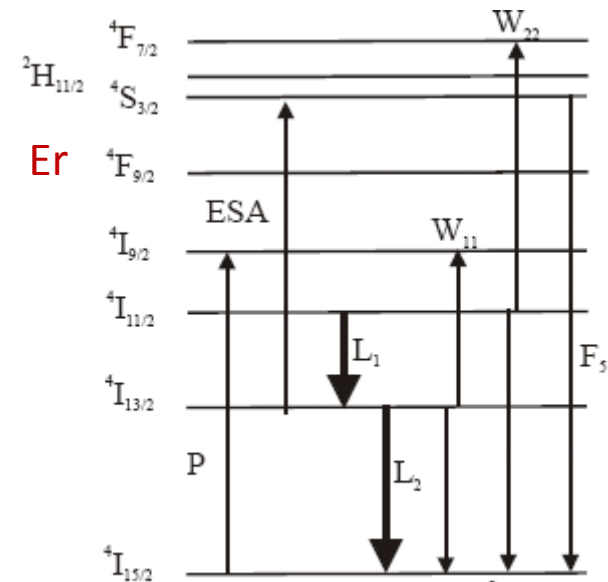


Figura 3.3.2: Energy level scheme of Er^{3+} :YAG

I laser della seguente tabella sono tutti a quattro livelli e presentano carattere vibronico.

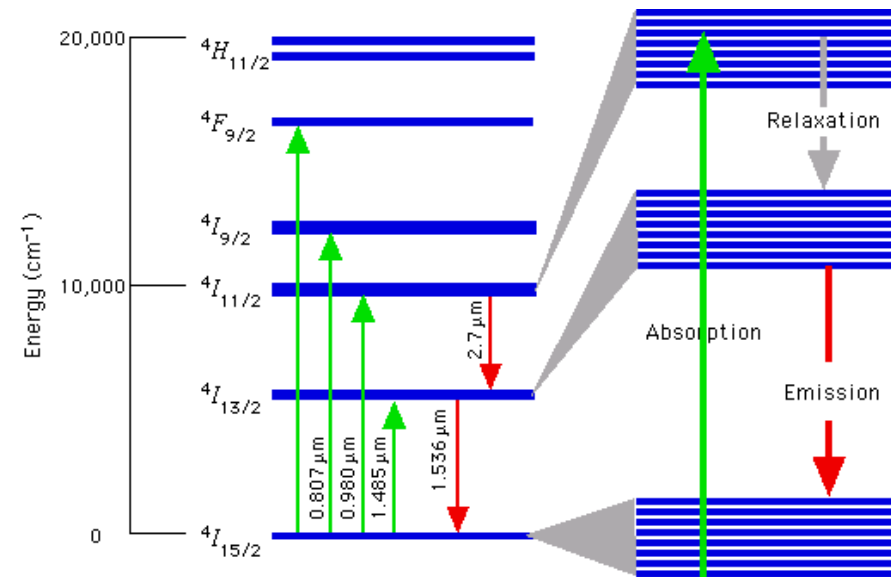
MATERIALE LASER	SORGENTE POMPAGGIO	MODO DI FUNZIONAMENTO	INTERVALLO DI ACCORDABILITÀ (NM)
Alessandrite	lampade ad arco	CW	730 - 810
Alessandrite	lampade flash	impulsato	701 - 858
Ce: YLF	laser a eccimeri KrF	impulsato	309 - 325
Co: MgF ₂	1320-Nd:YAG	impulsato	1750 - 2500
Cr: LICAF	laser o lampade	impulsato o CW	720 - 840
Cr: LISAF	laser o lampade	impulsato o CW	760 - 920
Cr: Smeraldo	laser	impulsato o CW	720 - 842
Cr: Forsterite	laser	impulsato o CW	1167 - 1345
Thulium: YAG	laser	CW	1870 - 2160
Ti: Zaffiro	laser	impulsato o CW	660 - 1180

Variant: vibronic lasers

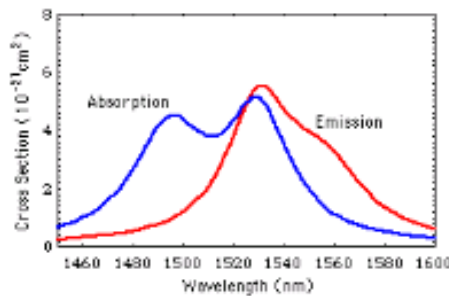
In this case the interaction with the matrix is used to broaden the discrete energy levels --> tunability & ability to produce ultra-short pulses (we'll see more in the following)

Ti:Sa is probably the most relevant example

Er-DOPED FIBER AMPLIFIER (EDFA LASER)



2. EDFA (Erbium Doped Fiber Amplifier): Er^{+3} randomly distributed in glass



The absorption and emission cross sections for the $4I_{15/2} \rightarrow 4I_{13/2}$ transition in Er^{+3} .

The active medium is in practice a doped matrix

The matrix can also be in the amorphous phase, e.g., glass (cheaper and with still reasonable thermal conductive properties, useful to withstand high power or high repetition rate operation)

Such amorphous matrix can also be prepared in the form of an optical fiber (which behaves like a light amplifier, for instance in the regeneration of TLC signals in the long haul transmission)

EXCIMER LASER I

Excimers (*Excited Dimers*) are unstable compound (typically diatomic, involving rare gases and halogen species, e.g., XeCl)

Excimers exist only in the excited state

- *population “automatically” inverted (the one at the ground state is virtually zero!)*
- *operation possible only in pulsed mode (pumping achieved with a pulsed discharge in a highly reactive gas mixture)*

2.7 Laser a Eccimeri

Il termine *eccimero* indica "dimero eccitato", cioè una molecola, composta da due specie chimiche, che esiste solo nello stato eccitato mentre nello stato fondamentale non risulta legata chimicamente. Nel senso più generale, indica una molecola biatomica o triatomica esistente soltanto nello stato eccitato.

Le molecole Xe_2 e He_2 sono un classico esempio di eccimeri. Queste infatti, una volta formatesi, tendono a decadere liberando energia; ritornano così allo stato energetico basso (non eccitato) ed alla configurazione di atomi indipendenti.

Sistema di pompaggio

Il pompaggio della miscela può avvenire tramite scarica elettrica, microonde oppure per mezzo di un fascio di elettroni.

Nel caso della scarica elettrica si ha un basso rendimento di eccitazione poiché solo il 5% dell'energia prodotta dalla scarica stessa può essere convertita in energia utile all'emissione laser. Inoltre l'instabilità delle scariche limita la lunghezza degli impulsi a poche decine di nanosecondi nonostante la struttura interna possa sostenere impulsi di centinaia di nanosecondi. Pregio di questo tipo di eccitazione è la relativa semplicità di realizzazione. Per avere una scarica uniforme e stabile

Potenza di uscita

Il laser a KrF può produrre impulsi di 300 ns di durata con frequenza di ripetizione fino a 1 kHz con potenze medie fino a 1 kW.

I laser a KrCl producono impulsi di energia e potenze dell'ordine di un decimo di quelli dei laser a KrF.

Per applicazioni generali che hanno bisogno di impulsi ultravioletti ad alta energia la scelta usuale cade sui laser a KrF o quelli a XeCl. I laser a XeCl sono meno potenti ma più soddisfacenti poiché non contengono fluoro (molto corrosivo), hanno lunghezze d'onda di emissione grandi (quindi basta una minor precisione nelle ottiche) ed il tempo di vita della miscela è molto elevato. Nei laser ad eccimeri l'energia dell'impulso decresce quando la frequenza di ripetizione supera un certo valore soglia, leggermente al di sopra del quale si ha la massima potenza media (Fig. 2.6.3).

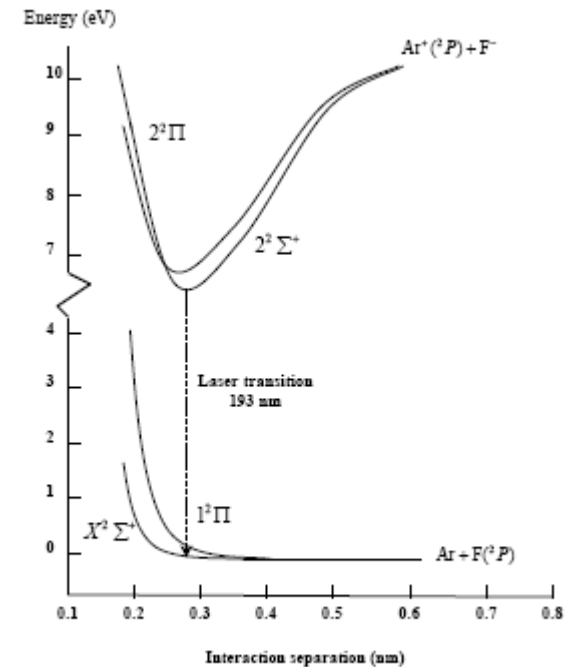


Fig. 2.6.1 Diagramma dell'energia potenziale dell'eccimero ArF. E' mostrato lo stato legato transitorio dell'ArF e la transizione laser a 193 nm.

Large peak energy due to the virtually very large gain
Emission in the UV precious for many applications (material treatment, **ablation**, surgery, **optical lithography** in micro-electronics)

Miscela attiva	Emissione (nm)
ArF	193
KrCl	222
KrF	248
XeF	308
XeCl	350
F ₂	157

EXCIMER LASER II

Cavità ottica

Uno degli specchi della cavità è altamente riflettente. L'alto guadagno di questo laser elimina il bisogno di uno specchio in uscita. Alcuni laser usano delle ottiche allo zaffiro. Si può inoltre inserire un reticolo di diffrazione nella cavità per sintonizzare le lunghezze d'onda d'uscita nella larghezza di banda del guadagno.

Potenza di uscita

Il laser a KrF può produrre impulsi di 300 ns di durata con frequenza di ripetizione fino a 1 kHz con potenze medie fino a 1 kW.

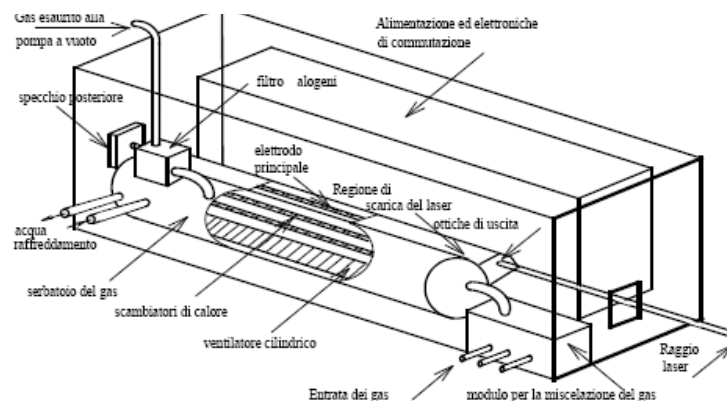
I laser a KrCl producono impulsi di energia e potenze dell'ordine di un decimo di quelli dei laser a KrF.

Per applicazioni generali che hanno bisogno di impulsi ultravioletti ad alta energia la scelta usuale cade sui laser a KrF o quelli a XeCl. I laser a XeCl sono meno potenti ma più soddisfacenti poiché non contengono fluoro (molto corrosivo), hanno lunghezze d'onda di emissione grandi (quindi basta una minor precisione nelle ottiche) ed il tempo di vita della miscela è molto elevato. Nei laser ad eccimeri l'energia dell'impulso decresce quando la frequenza di ripetizione supera un certo valore soglia, leggermente al di sopra del quale si ha la massima potenza media (Fig. 2.6.3).

Nel caso della scarica elettrica si ha un basso rendimento di eccitazione poiché solo il 5% dell'energia prodotta dalla scarica stessa può essere convertita in energia utile all'emissione laser. Inoltre l'instabilità delle scariche limita la lunghezza degli impulsi a poche decine di nanosecondi nonostante la struttura interna possa sostenere impulsi di centinaia di nanosecondi. Pregio di questo tipo di eccitazione è la relativa semplicità di realizzazione. Per avere una scarica uniforme e stabile il mezzo viene pre-ionizzato (con raggi UV o X) (Fig. 2.6.2).

Big lasers!

Pulse energy up to several Joules (in 10 ns pulses)
--> huge intensity!

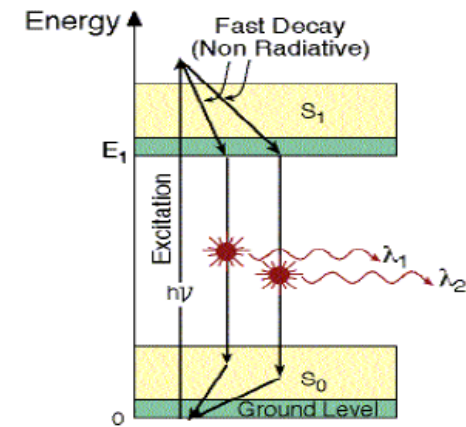


DYE LASERS I

Laser action in a solution of an organic dye molecule **chloroaluminium phthalocyanine** was demonstrated in **1966** by Sorokin and Lankard and independently in **3,3'-diethylthiatricarbocyanine bromide** in methanol by Schaefer et al.

These were the **first dye liquid lasers** and were excited by a pulsed **ruby laser** at 694nm and gave laser emission near **755nm**. These discoveries were quickly followed over the next few years by demonstration of laser operation in **many organic dye molecules** using alternative excitation sources.

Continuous operation of the dye laser was not achieved **until 1970** when an **argon ion laser** operating at **515 nm** was used to excite **rhodamine 6G in water solution**. The availability of shorter wavelength lasers as pump sources, such as the **337.1nm nitrogen laser**, the excimer lasers with UV output or the higher harmonics of solid-state lasers, enabled **dye lasers** operating at **shorter wavelengths** to be devised. The **strong absorption** and **emission cross-sections** of the dye molecules of about 10^{-16}cm^2 and the corresponding lifetimes of the laser emitting state of a **few nanoseconds** means that a **high pumping intensity** is required. This is achieved optically by **intense flashlamps** or by **another laser**. The development of the dye laser is closely linked generally to the evolution of laser technology over the last forty years.



Dye molecules are typically very big and heavy molecules with many possible degrees of freedom leading to very many (broad) energy levels

Many optical transitions are possible

Tunability can be achieved in relatively large ranges in the visible-near IR

By changing the dye solution, almost all the visible range can be covered (but not inn truly continuous mode – transitions are discrete in energy)

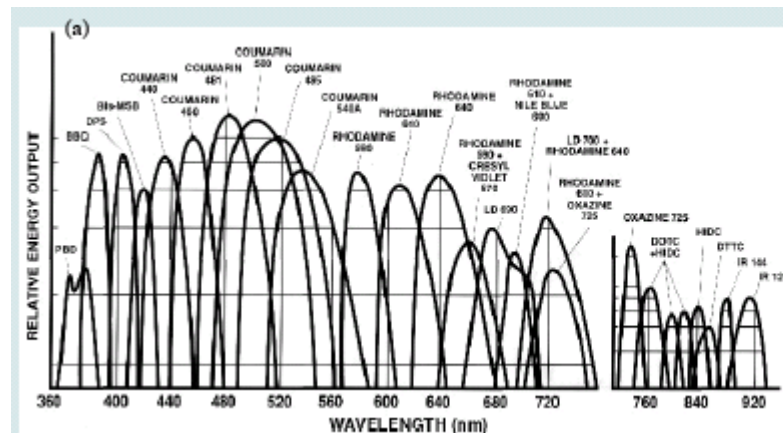


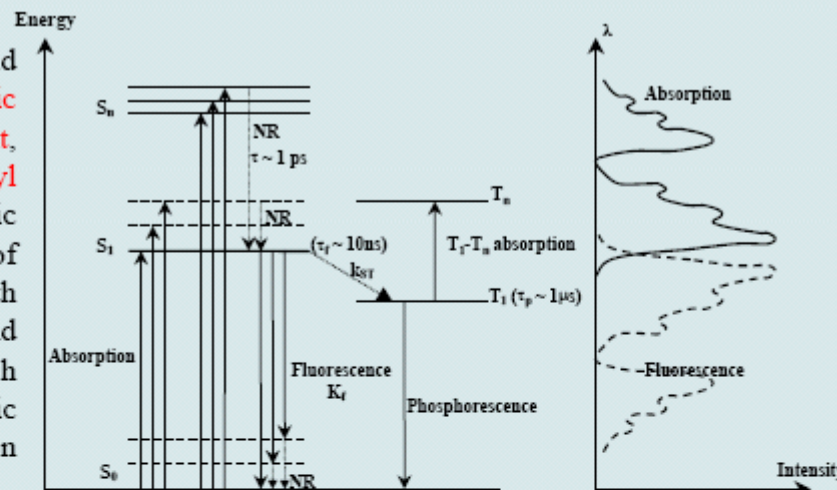
Figure 3. Tuning performance of dye lasers with pumping by (a) **nitrogen lasers** (Exciton Inc.).

Optical pumping (typically, with a pulsed pump laser, e.g., excimer, Nd:YAG, N₂) is needed

DYE LASERS II

Basic principles

The most common liquid state laser contains **organic dye** molecules in a **solvent**, typically **ethyl** or **methyl alcohol** or **water**. Organic dyes possess a backbone of carbon atoms with conjugated double bonds and delocalised π electrons which confer their characteristic absorption and emission properties.



Absorption and emission characteristics of dye molecules

The electronic energy levels of a dye molecule are shown in Figure 1. The outer $2s^2 2p^2$ electrons of the carbon atom are hybridized into three sp^2 trigonal orbitals to form planar and structural bonds. The fourth p electron is in a delocalized π molecular orbital; in a carbon chain these form two planar distributions above and below the molecular plane and which are able to move freely within the chain. The π electrons determine the electronic states for the outer electrons. The states are simply arranged into a set of singlet states ($S_0, S_1, S_2 \dots$) having a total spin equal to zero, and a set of triplet states having a total spin of one. To each electronic state there corresponds molecular vibrational modes (indicated in Figure 1) and also rotational modes.

Dye lasers very diffused in the 70-90's

Many applications:

- analytics (laser spectroscopy)
- dermatology
- fundamental physics research

Cumbersome operation:

- need of preparing solutions
- unstable operation (and limited in time, the solution burns)
- need for another laser to be used as a pump
- poor or very poor overall efficiency
- CW operation rather unstable

Pulsed dye lasers

The pulsed dye lasers produce tunable, narrow bandwidth, high energy pulses. Pulsed dye lasers at up to a **few tens of W average power** may be excited by several pump lasers, including nitrogen, Nd:YAG, excimer and copper vapour lasers. These provide the necessary high pump intensity around **100 kWcm⁻²** while operating on a time scale in which triplet-triplet absorption and thermal distortion of the laser medium is minimal.

Pump Source	Tuning Range (nm)	Pulse Duration (ns)	Peak Power (W)	Pulse Energy (mJ)	Repetition Rate (Hz)	Average Power (W)
Flashlamp	300-800	300-10 ⁴	10 ² -10 ⁴	< 5000	1-100	0.1-200
Ar ⁺ or Kr ⁺	400-1100	CW	CW	—	CW	0.1-5
N ₂	370-1020	1-10	<10 ⁵	<1	<10 ³	0.01-0.1
Excimer	370-985	10-200	<10 ⁷	≤300	20-2000	0.1-10
Nd:YAG	400-920	10-20	10 ⁵ -10 ⁷	10-100	10-30	0.1-1
CVL	530-890	30-50	10⁴-10⁵	≈1	≈10⁴	≤10

CONCLUSIONS

Pumping a quantum system can actually lead to inversion of population which can lead in turn to photon amplification

Since stimulated emission is involved, this gives motivations to the name IASer, hence to the laser operation

Pumping schemes typically involve three or more energy levels

Pumping strategies have been evolved during the years, along with the evolution of technologies (and in view of specific applications)

Many laser active media and many lasers are commercially available to cover a wide range of technical needs

Ampia gamma di lunghezze d'onda, potenze, modalità di operazione (continua o impulsata) disponibili sfruttando questi mezzi attivi

Careful, however: amplification is not yet enough to fully explain the laser operation!! (this is the story we will see in the next slides!)

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