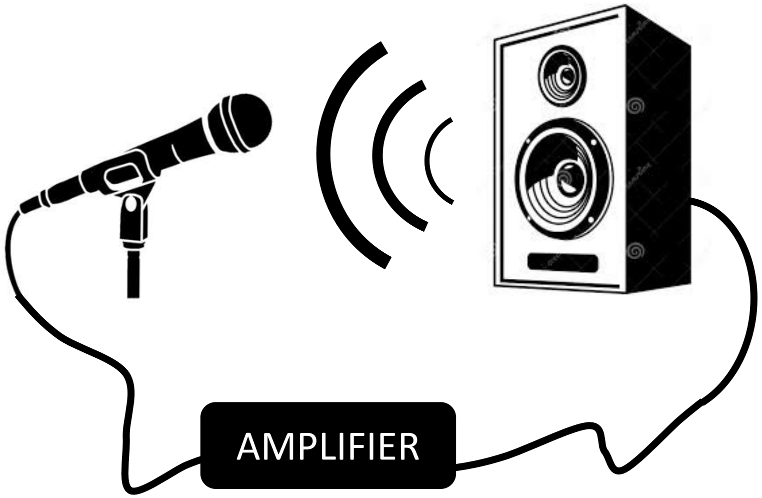
LASERs

working principles and technology

LASER - DEFINITION



Light
Amplification by
Stimulated
Emission of
Radiation

A laser can be defined as a "photon amplifier"
Optical amplification is obtained via a phenomenon called stimulated emission
The amplification process leads to emission of a "special type of light"

- A laser is an optical source that emits photons in a coherent beam
- In analogy with optical lasers, a device which produces any particles or electromagnetic radiations in a coherent state is called "Laser", e.g., Atom Laser.
- In most cases "laser" refers to a source of coherent photons i.e., light or other electromagnetic radiations. It is not limited to photons in the visible spectrum. There are x-rays, infrared, UV lasers etc.

Layout

–Introduction

–Properties of Laser Light

–Basic Components of Laser

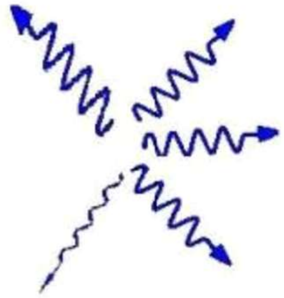
–Laser operation

–Types of Lasers

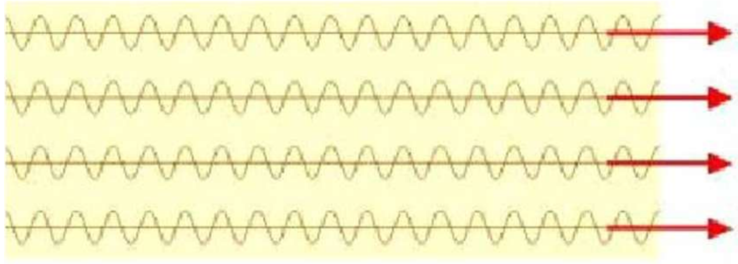
–Laser Applications

Properties of Laser Light

- The light emitted from a laser is ***monochromatic***, that is, it is of one color/wavelength. In contrast, ordinary white light is a combination of many colors (or wavelengths) of light.
- Lasers emit light that is highly ***directional***, that is, laser light is emitted as a relatively narrow beam in a specific direction. Ordinary light, such as from a light bulb, is emitted in many directions away from the source.
- The light from a laser is said to be ***coherent***, which means that the wavelengths of the laser light are in phase in space and time. In ordinary light photons feature a mixture of many phases



Ordinary Light



Laser Light

Laser Theory
Energy States

All things in nature prefer to go to the lowest energy state available to them. Atoms, molecules, materials tend to prefer to always stay in their ground state, unless some intervening force causes them to reach an excited state. In the language of lasers, any process that feeds energy into a collection of atoms or molecules and causes them to vacate their ground state is referred to as an energy pump.

In most lasers electricity is used, by one mechanism or other, to pump atoms out of their ground-state into some excited state. In some lasers optical pumping is the mechanism that is used to cause excitation (a light source generates photons that excite the atoms/molecules in the lasing medium and cause them to go into an excited state).

Laser Theory

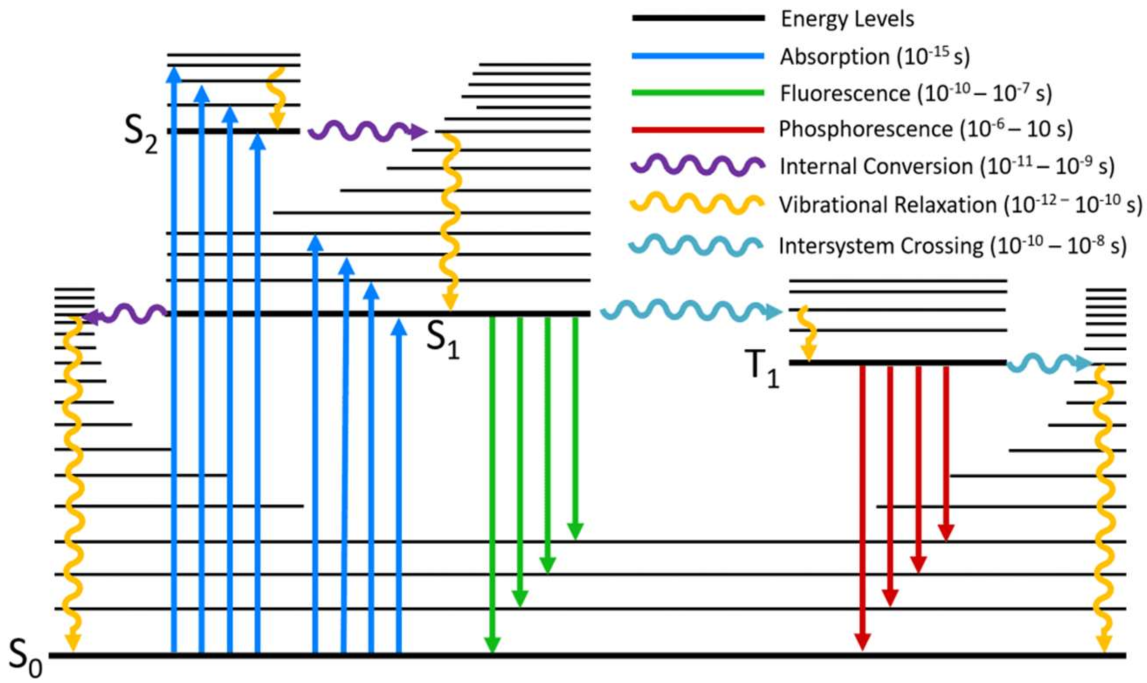
Energy State Kinetics

The most stable of states is the ground state.

Excitation (absorption of energy to form excited states) occurs "instantaneously“.

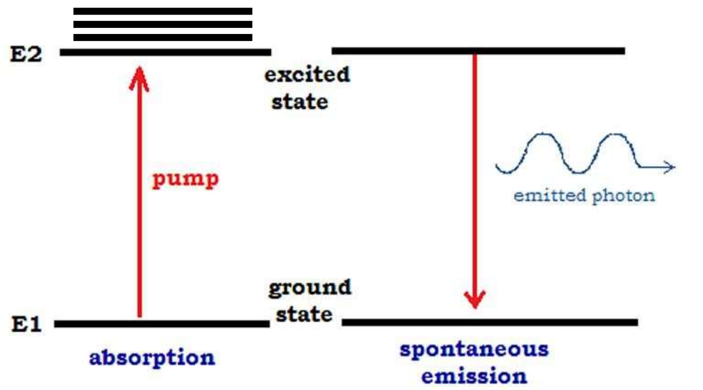
De-excitations can lag by a measurable time interval that depends on the properties of the excited state. The time that it spends, on average, in that excited level is called the lifetime of that state. Lifetimes can vary in duration, typically a few nanoseconds (10^{-9} s), or as short as a picosecond (10^{-12} s) or as long as a few milliseconds (10^{-3} s).

Long-lived states are referred to as meta-stable states.



(Warning: simplified diagram!)

Laser Theory
Energy State Populations

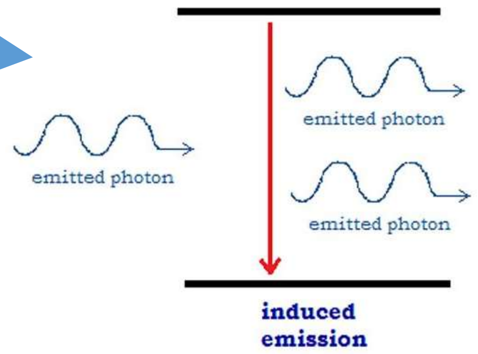


Pump (absorption): can occur electrically or optically (absorption of a photon)

Radiative emission: can be spontaneous or stimulated.

Spontaneous emission refers to when the excited atom de-excites, spontaneously and thus “randomly” distributed in time, direction of travel, phase, energy and polarization.

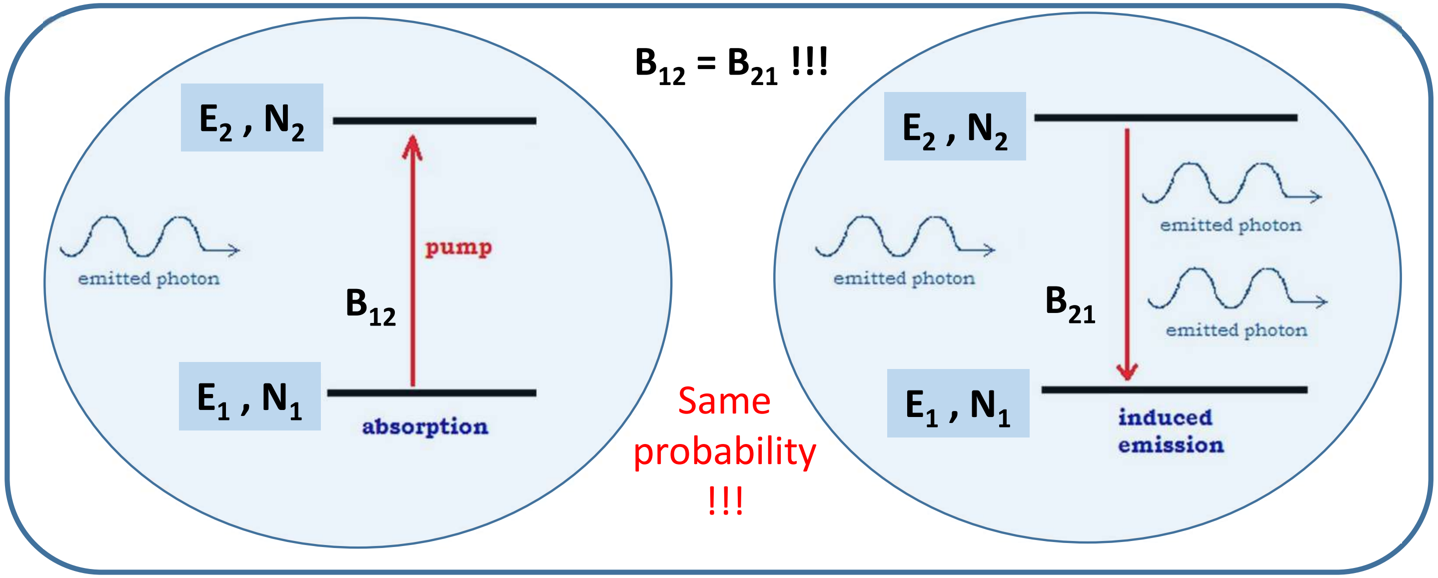
Stimulated (or induced) emission was first theorized by Albert Einstein in 1917. A stimulating photon must be present, whose energy must exactly match the allowed energy of the transition. The newly emitted photon will have the same energy as the stimulating one, it will travel in the same direction, have the same polarization and phase. It will be identical.



In stimulated emission, 1 photon interacts with an excited state to yield a “clone” photon. These two photons can then interact with two more excited states and produce a total of 4 clone photons. >>> This is an amplification mechanism!

Laser Theory

Population inversion



absorption	$Mol1 + h\nu \rightarrow Mol2$	$\left(\frac{dN_1}{dt}\right)_{abs} = -h\nu B\Phi N_1$	>> a «stimulating» photon will be adsorbed (**depletion of photons**)
spontaneous emission	$Mol2 \rightarrow Mol1 + h\nu$	$\left(\frac{dN_1}{dt}\right)_{spe} = +AN_2$	
stimulated emission	$Mol2 + h\nu \rightarrow Mol1 + 2h\nu$	$\left(\frac{dN_1}{dt}\right)_{ste} = +h\nu B\Phi N_2$	>> a «stimulating» photon will produce a new photon (**amplification of photons**)

***A* and *B* are the Einstein coefficients**

Φ is the photon density (photons / cm^3)

N_1 and N_2 are the populations of the two energy levels (molecules / cm^3)

It is to be noted that absorption and stimulated emission have the <u>same</u> kinetic rate constant, the *B* coefficient.

Laser Theory
Population inversion

To make a laser we need to not only excite the components in the laser medium, but somehow encourage them to undergo a decay through stimulated emission. In stimulated emission a passer-by photon (with an energy exactly equal to the transition energy) stimulates an excited atom to emit a photon, identical to the passer-by photon.

The problem with this is that the same passer-by photon could instead get absorbed by a de-excited atom. So, we need clever procedures to enhance the probability of stimulated emission compared to absorbance; i.e. we need to generate a population inversion.

Einstein predicted stimulated emission in 1917, it was not found experimentally for over 10 years and took over another 30 years just to predict the possibility of a laser.

In the absence of a pump the atoms or molecules are almost all in their ground state.

Then $N_1 = N_2 = ... = 0$, and $N_{ground\ state}$ = total number of all atoms/molecules in the medium.

Once the pump is turned on it will start exciting atoms/molecules from the ground state to the excited states. But excited atoms de-excite quickly and return to their ground states by spontaneous emission:

$$N_{ground\ state} \gg N_{any\ other\ state}$$ ← PROBLEM!!

Credits prof. Claudio Degli Esposti

Laser Theory

Population inversion and threshold condition

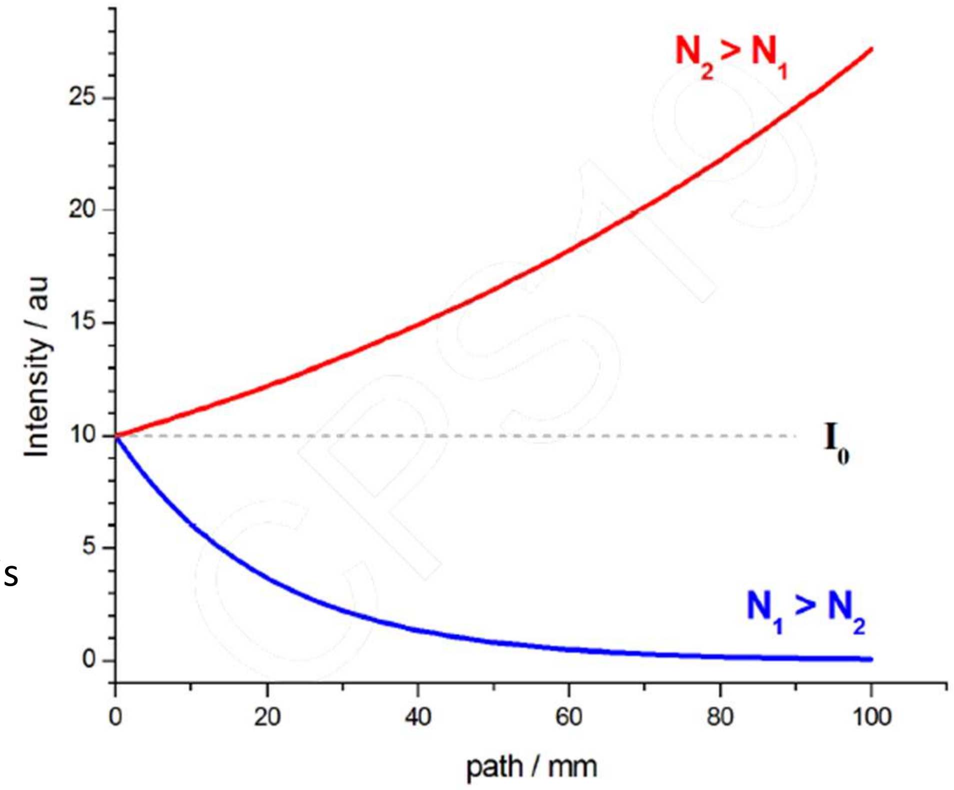
I_0 is the intensity of the input beam, and I the intensity of the beam at the end of an interaction path of length l.

In which way I_0 and I are related ?

$$I = I_0 \, exp[-\frac{h\nu}{c} B(N_1 - N_2) \, l \,]$$

If $N_1 > N_2$, then $I < I_0$, because absorption is more likely.

If $N_2 > N_1$, then $I > I_0$, because stimulated emission is more likely.



Threshold Condition

Here, stimulated emission is the "gain" of a laser, while absorbance is a "loss". Laser action will be achieved if $I > I_0$, i.e., if, in a round trip:

Gain > Loss

This is called achieving **Threshold**.

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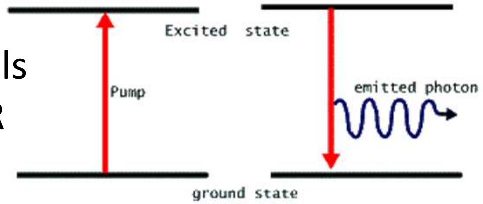
Laser Theory
Population inversion

For stimulated emission a "passer-by" photon must approach the excited atom before it de-excites via spontaneous emission.
Typically, a photon emitted by the spontaneous emission serves as the seed to trigger a collection of stimulated emissions.
The excited state must have a relatively long lifetime >> meta-stable state.
The likelihood of absorption of the "passer-by" photons must be minimized (population inversion).

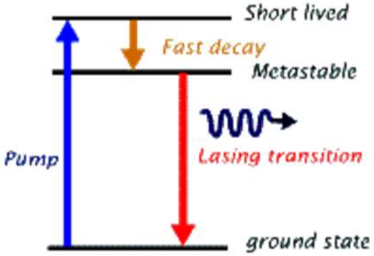
Laser Theory

Population inversion

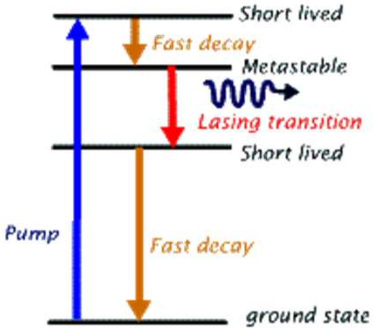
2 levels
LASER



3 levels
LASER



4 levels
LASER



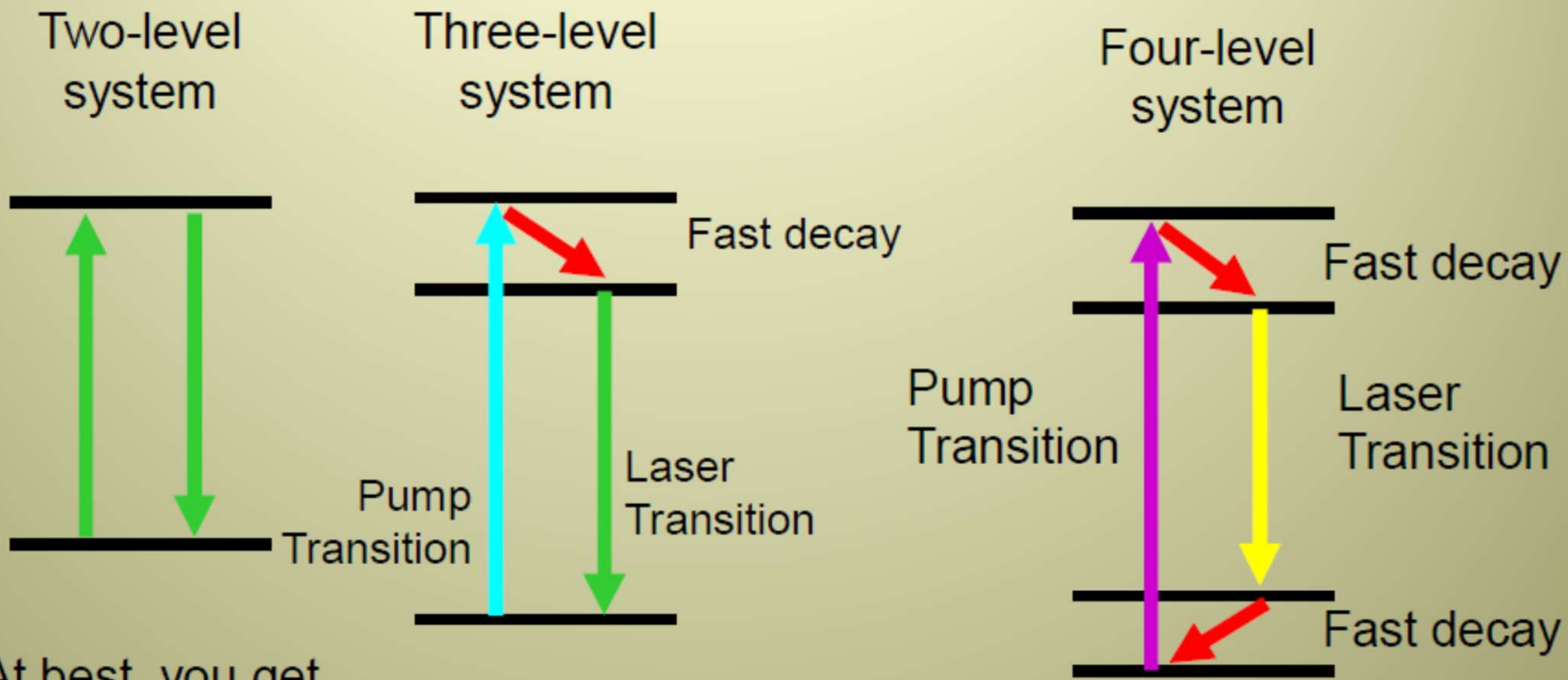
Population Inversion in Two, Three, and Four-level systems

Achieving population inversion **in a two-level system** is not very practical. Very strong pumping (similar to reversing the flow of water in a water fall). Very energy costly and inefficient. It would work only in jolts: *once the population inversion is achieved the laser would lase. But immediately it would end up with more atoms in the lower level.*

The first laser that was demonstrated to operate was a **three-level laser**, Maiman's ruby laser.
Excitation from the ground state to the second excited state. This state is a rather short-lived state, so that the atom quickly decays into the first excited level. The first excited state is a long-lived (i.e. metastable) state which allows to "wait" for the "passer-by" photon while building-up population of this state.
In addition pump and lasing transitions are different in energy, so pumping can be very strong without interfering with stimulated emission.
Yet, the fact that the lower lasing transition is the ground state makes it rather difficult to achieve efficient population inversion. In a ruby laser this task is accomplished with *a very strong pulsating light source*, called a flash lamp.

To achieve a **continuous beam of laser light a four-level laser** is required.
Here, the lower laser level is not the ground state. As a result, even a pump that may not be very efficient could produce population inversion, so long as the upper level of the laser transition is longer lived than the lower level. Of course, all attempts are made to design a pump that maximizes the number of excited atoms. A typical four-level laser is the helium-neon (He-Ne) gas laser, or dye lasers.

Two-, Three-, and Four-Level Systems



At best, you get equal populations. No lasing. (With optical pump)

If you hit it hard, you get lasing.

Lasing is easy!

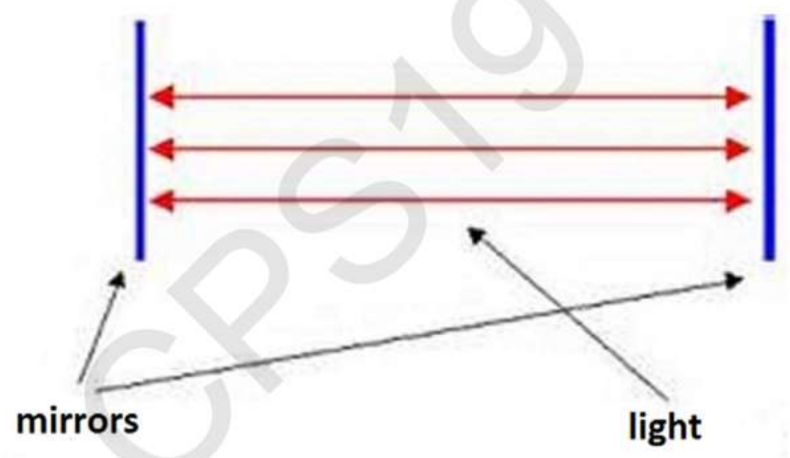
Laser Theory
The resonator

Even when $N_2 > N_1$, the excited molecules could preferentially emit by spontaneous emission, not useful to obtain amplification.

When population inversion is achieved, lasing is possible. But in which conditions stimulated emission actually overcomes spontaneous emission?

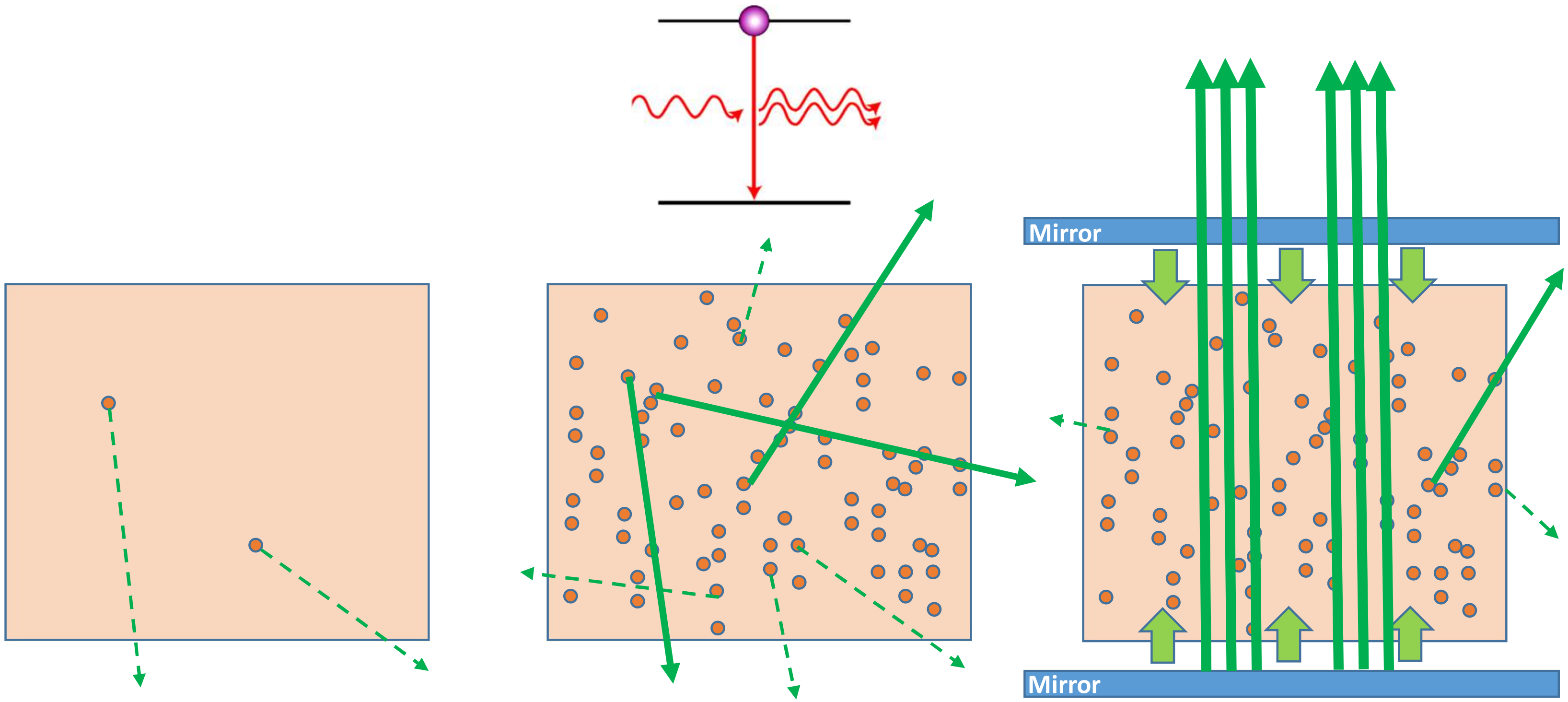
OPTICAL RESONATOR

One can make stimulated emission more important than spontaneous emission putting the molecular system inside a resonant cavity, that is a space delimited by two mirrors.



Multiple reflexions along the resonator axis multiplicate the stimulated emission events, so that a unidirectional beam with a very large photon density is created.

Laser: from spontaneous to stimulated emission

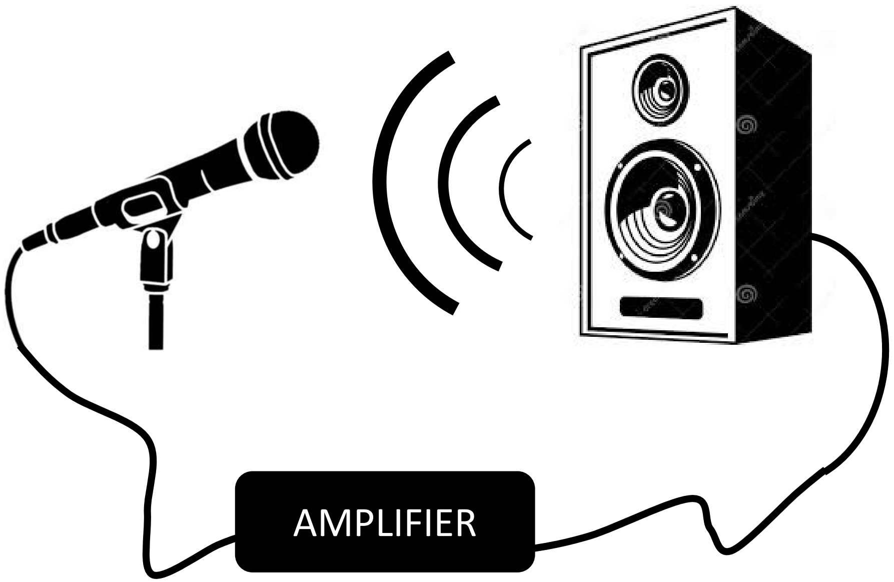


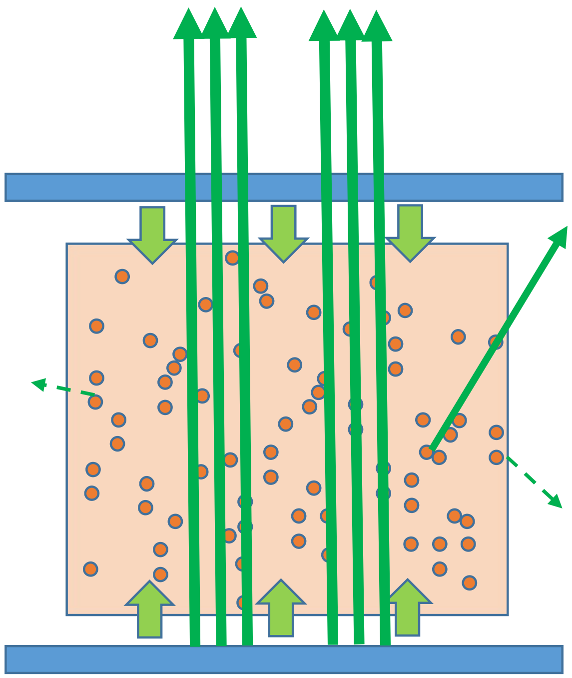
Fluorescence
(**Spontaneous** Emission)

Stimulated Emission
ASE
(Amplified Spontaneous Emission)

LASER
(light **amplification** by stimulated emission of radiation)

Lasers





LASER
(light **amplification** by stimulated emission of radiation)

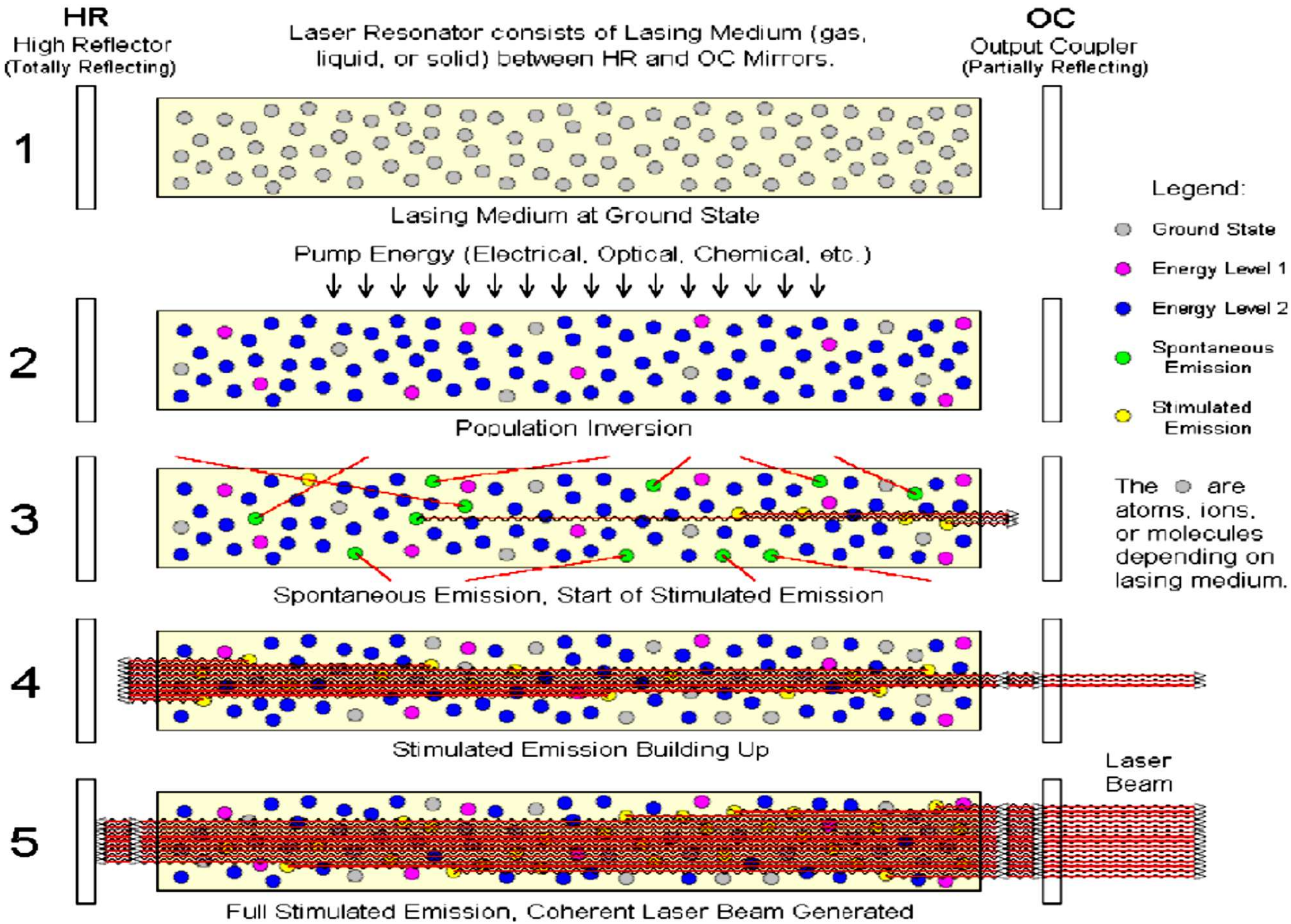
Laser Startup

How does a laser start to work ?

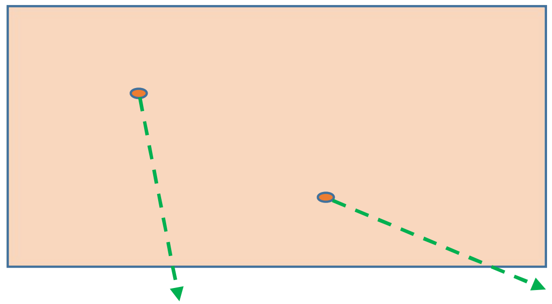
1- The pumping system creates the necessary population inversion in the active medium, which means that a large number of excited molecules are produced.

2- The excited molecules start to decay radiatively by spontaneous emission.

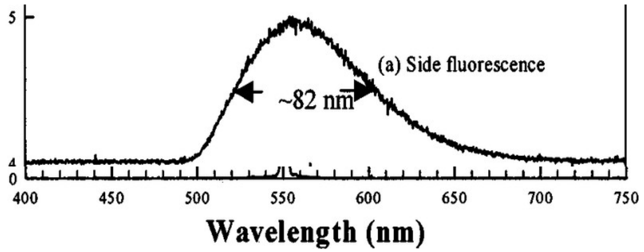
3- Spontaneous emission is omnidirectional, and some photons will be certainly emitted in the direction of the optical axis of the resonator. Stimulated emission can start, and multiple reflections lead to the formation of the laser beam.

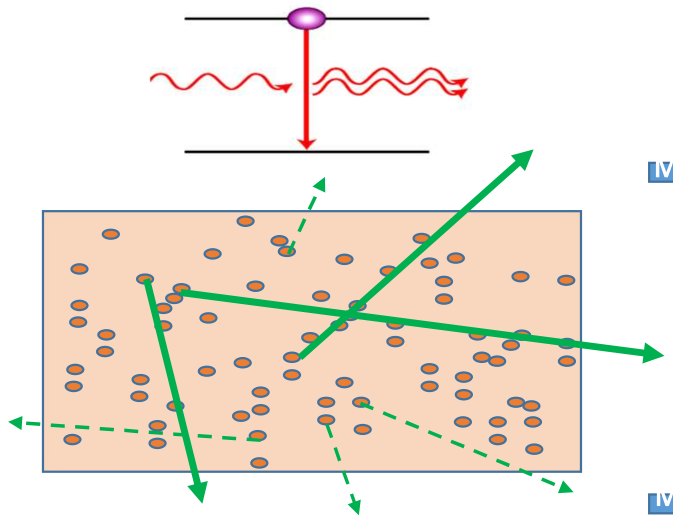

HR
High Reflector
(Totally Reflecting)
Laser Resonator consists of Lasing Medium (gas, liquid, or solid) between HR and OC Mirrors.
OC
Output Coupler
(Partially Reflecting)
1
Lasing Medium at Ground State
Pump Energy (Electrical, Optical, Chemical, etc.)
2
Population Inversion
3
Spontaneous Emission, Start of Stimulated Emission
4
Stimulated Emission Building Up
5
Full Stimulated Emission, Coherent Laser Beam Generated
Legend:
Ground State
Energy Level 1
Energy Level 2
Spontaneous Emission
Stimulated Emission
The are atoms, ions, or molecules depending on lasing medium.
Laser Beam

Properties of Lasers

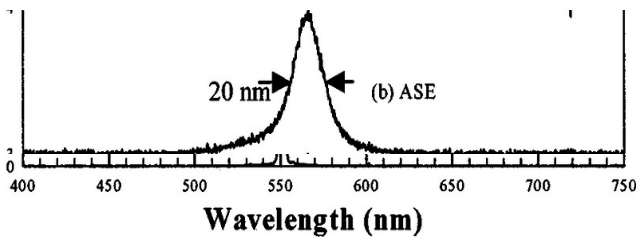


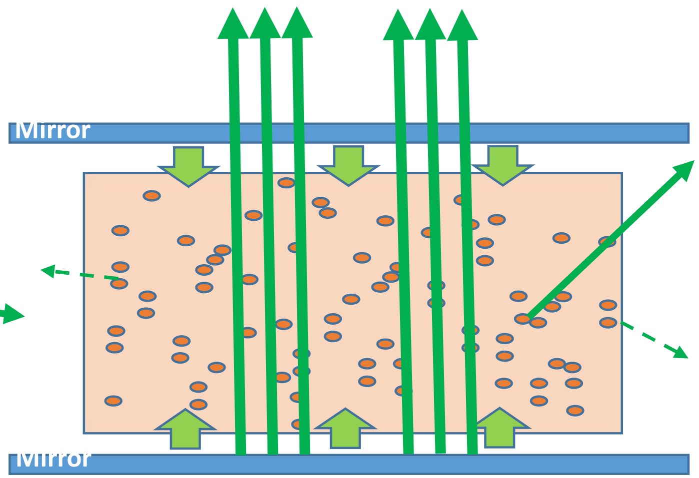
Fluorescence
(**Spontaneous** Emission)



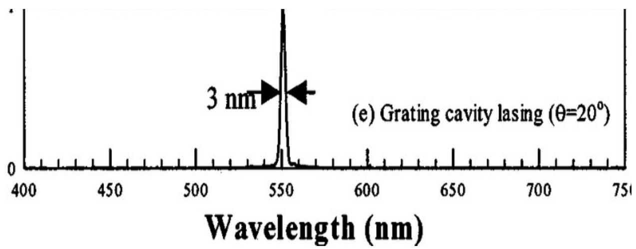


Stimulated Emission
>>
ASE
(Amplified Spontaneous Emission)





LASER
(light **amplification** by stimulated emission of radiation)



Laser Theory
The resonator

- Laser resonant cavities usually have two flat or concave mirrors that reflect photons back and forth, elongating the photon path by repeated passes, so that stimulated emission continues to build up more and more laser light (exponential growth).
- The term used for amplified light is gain (*number of additional photons produced per unit path length)*.
- *The "back" mirror is made as close to 100% reflective as possible, while the "front" mirror typically is made only 95 - 99% reflective* so that the rest of the light is transmitted by this mirror and leaks out to make up the actual laser beam outside the laser device.
- The resonant cavity thus accounts for the directionality of the beam, since only photons travelling in the direction of the axis between the facing mirrors lead to amplification. Once the beam escapes through the front mirror it continues as a well-directed laser beam (collimated over long distances).
- Why is the resonant cavity called by that name? At a resonant frequency, two waves can add or cancel all the time. The mirror separation distance, L, must be equal to a multiple of half a wavelength of light, just as in the case of a vibrating string: $L = n \lambda / 2$. Only a few so-called laser modes or laser resonant frequencies can be amplified in a laser.

Laser Components and their Classification

three primary **Laser components**:
- Medium
- Pump
- Resonant Cavity

Active Medium

Major determining factor of the wavelength of operation and other properties of laser.

• laser medium can be gaseous, liquid, or a solid. These could include atoms, molecules, or materials.

• The gain medium could be solid crystals such as ruby or Nd:YAG, liquid dyes, gases like CO2 or Helium-Neon, and semiconductors such as GaAs.

Pumping Mechanism

It provides energy to produce a population inversion.

• three different laser pumps: electromagnetic, optical, and chemical.

• Pump sources include electrical discharges, flash lamps, light from another laser, chemical reactions.

Optical Resonator

It elongates the path travelled by photons in the laser medium, enhancing the amplification factor.

• Responsible for directionality (collimation) of lasers

• One of the mirrors reflects essentially 100% of the laser light while the other reflects less than 100% of the laser light and transmits the remainder.

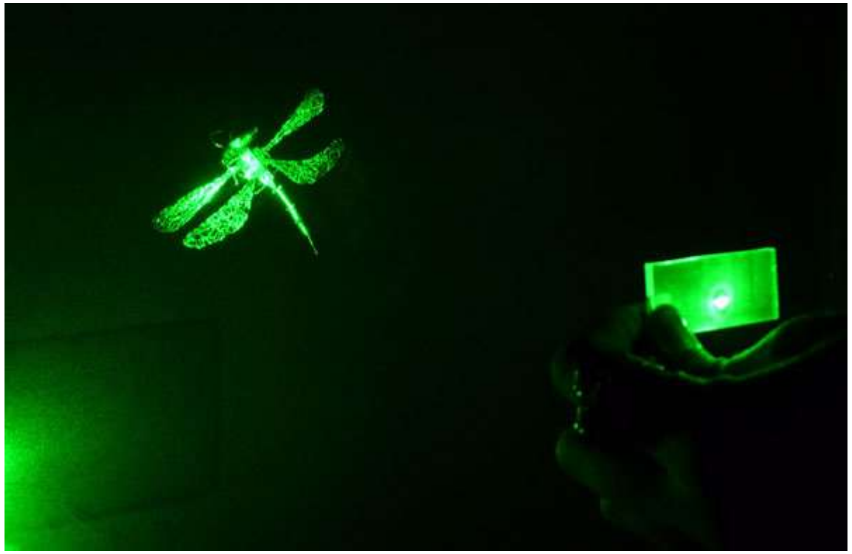
Properties of Laser Beams

1 - directionality ► optical reading , remote sensing , spatial control

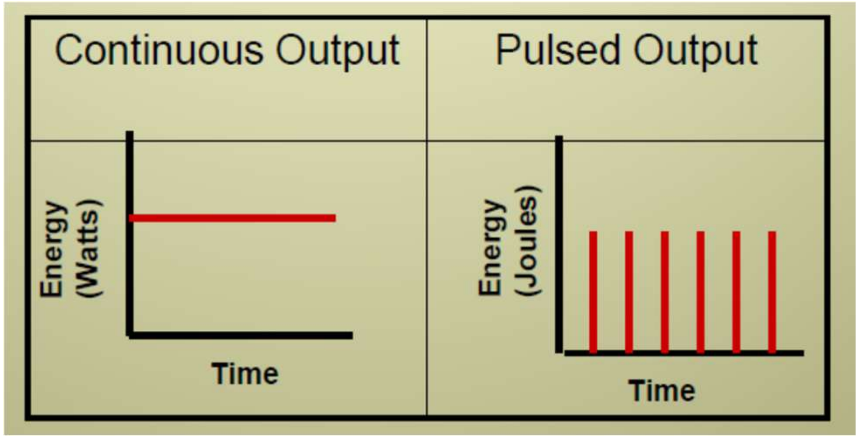
2 - high power ► material processing , laser surgery

3 - monochromaticity ► selectivity, high resolution spectroscopy, Raman

4 - coherence ► holography



Laser Beam Output



Time behavior of a laser affects its **power output** and **mode of emission** - continuous wave or pulsed

- **CW laser**- emits a continuous beam of light as long as medium is excited

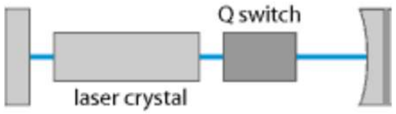
It is possible when the pumping system is able to preserve the population inversion constantly during the laser emission (4-levels, He-Ne laser, Ar^+ laser, Nd:YAG laser, CO_2 laser)

- **Pulsed laser**- emit light only in pulses- from femtoseconds to second

When population inversion preserved only for a very short time during the laser emission (3-levels, self-terminating lasers: ruby laser, N_2 laser). If convenient, a cw laser can be forced to the pulsed behavior by means of suitable techniques

  - Q-switched laser - pulses from micro to nanosecond
  - Mode-Locked laser - pulses from pico (10^{-12} s) – to femtoseconds (10^{-15} s)

Laser: Q-switching



Q-switching is a way of obtaining ***short*** (ns) and ***powerful*** (up to MW) pulses of laser.

Q refers to **quality factor** of the laser resonator:

- High Q = Low losses
- Low Q = High losses

The term Q-switching refers to an abrupt switching of the cavity Q from low value to a high value.

Methods of Q-switching:

- **Active Q-switching**

1. Mechanical devices: shutters, chopper wheel, spinning mirror
2. Electro-optic device: Pockel cells and kerr cells.
3. Acousto-optic device

- **Passive Q-switching**

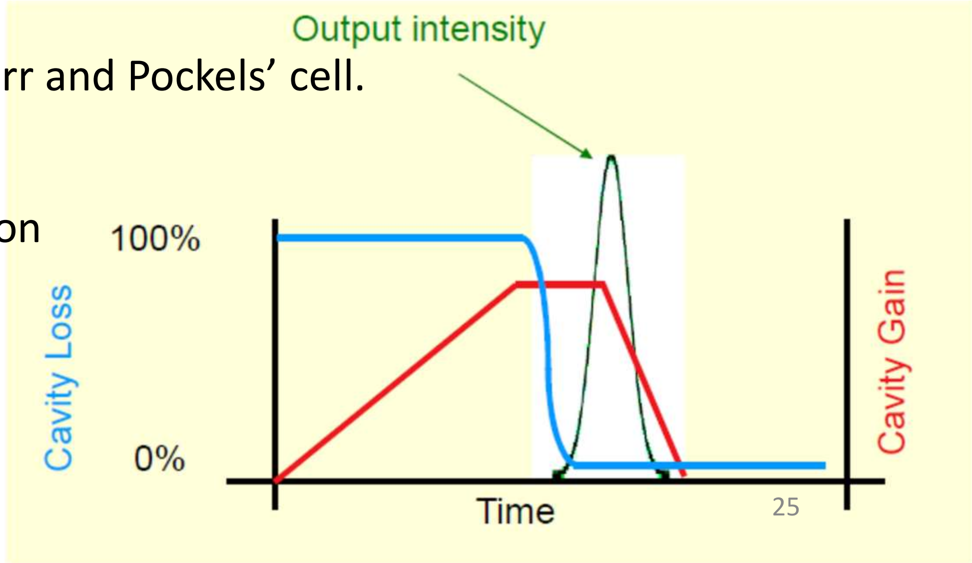
1. A saturable absorber

Techniques for Q switching

Using a mechanically driven device
- A rotating prism or mirror
- Rotate one of the mirrors about an axis perpendicular to the laser
- Rotating speed cannot be made very large
- Q switching does not take place instantaneously

Electro-optical Switches
- Light passes through a polarizer and an Electro-optic cell (control phase or polarization of laser beam)
- When appropriate voltage is applied- the material inside the cell becomes birefringent
- By varying the voltage – cell blocks or transmits beam.
- Two kinds of electro-optics switches are used-namely Kerr and Pockels' cell.

Passive Q- switching
- Initially light output absorbed by dye-preventing reflection
- After exciting the dye, light is allowed to pass
- Now reflection from mirror is possible
- Results in rapid increase in cavity gain

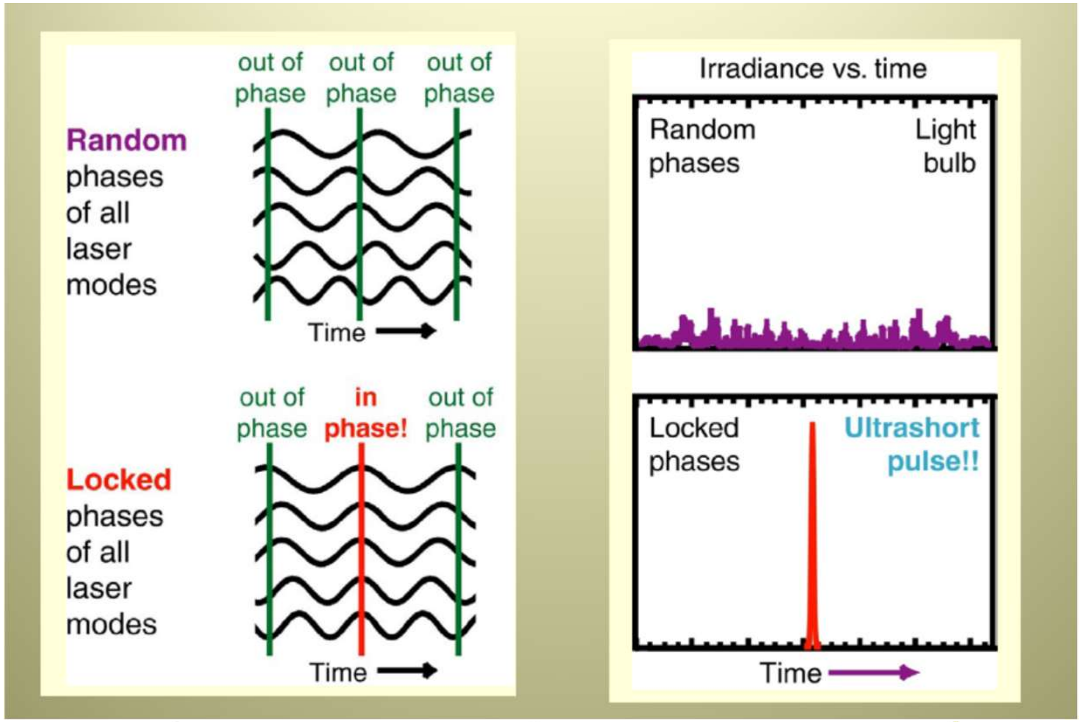


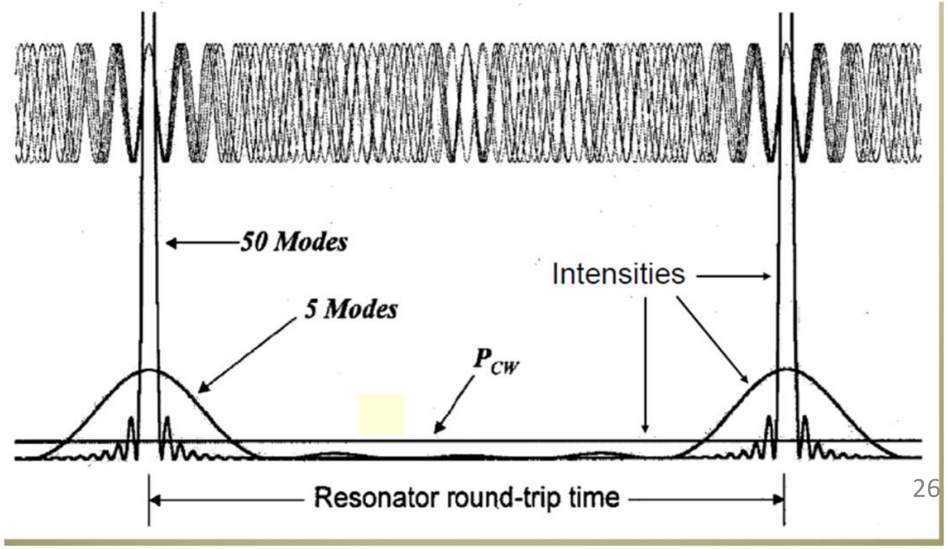
Laser: Mode-Locking

Mode-locking generates ultrashort optical pulse (range of femto-second 10^{-15} s).

Principle of Mode-Locking

- locking together the phases of all oscillating axial laser modes - having slightly different frequencies.
- Interference between these modes causes the laser light to be produced as a train of pulses.





Physical Properties of Laser

1. **Energy-** the amount of work accomplished – measured in joules

2. **Power-** Rate of energy expenditure – measured in joules per second or Watts (1J/s =1 W)

3. **Fluence - energy density-** amount of energy delivered per unit area - irradiance multiplied by the exposure time (J/cm^2).

4. **Irradiance- power density-** power of laser per unit area ($J/s/cm^2$).

Some laser output calculation

Pulses a and b each have N photons emitted by a laser, then we could easily calculate the pulse energies:

pulse energy = (number of photons in the pulse) x (energy of a single photon)

$= N \times (h\nu) = N \times (hc/\lambda) = N \times \{ (6.63 \times 10^{-34}) (3.00 \times 10^{8}) / (694.3 \times 10^{-9}) \}$

$= N \times (2.87 \times 10^{-19})$ Joules.

Alternatively, for a 10 J pulse, we could calculate the number of photons in each pulse:

number of photons = N = (pulse energy) / (energy of a single photon)

$N = (10) / (2.87 \times 10^{-19}) = 3.5 \times 10^{19}$.

The top pulse creates "less energy for a longer time" while the lower one creates "more energy for a shorter time". Since power is defined as:

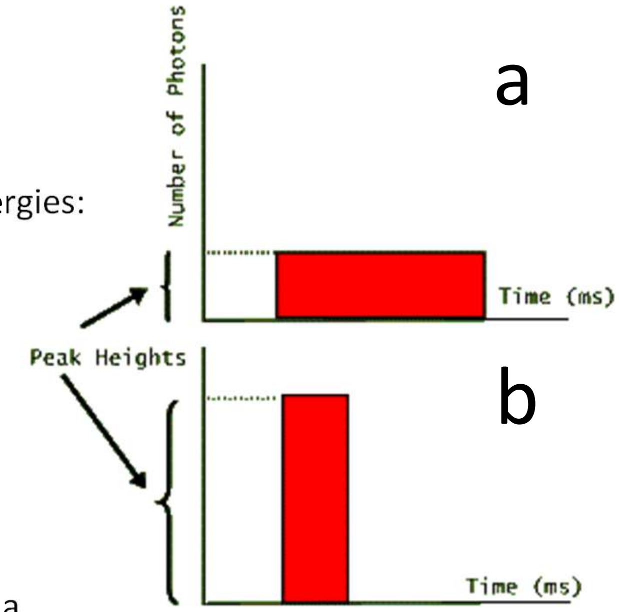
power = (energy) / (time) (***with units of 1 Watt = 1 Joule / 1 second***)

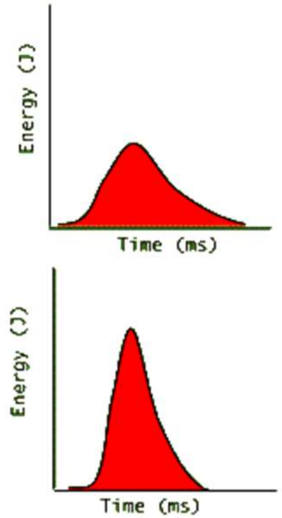
Then the pulse shown on the lower graph has much more power than the top one. This is called the pulse power, or the peak power.

For comparison with a cw laser it is convenient to average the energy of the pulse over not just its duration, but also over the time that the laser is on but there is not light emitted from it. To do this, all we need do is divide the total pulse energy by the time interval from when a pulse begins until the time that the next pulse begins; i.e. the "pulse-to-pulse time":

average power = (pulse energy) / (pulse-to-pulse time)

Pulsing a laser (e.g. with Q-switching) is a way to achieve large peak power.





Types of Laser

Lasers are usually classified in terms of their active (lasing) medium. Major types are:

• **Solid-state lasers** have lasing material distributed in a solid material (such as ruby or neodymium: yttriumaluminum garnet "Nd:YAG"). Flash lamps are the most common power source. The Nd:YAG laser emits infrared light at 1.064 micrometers.

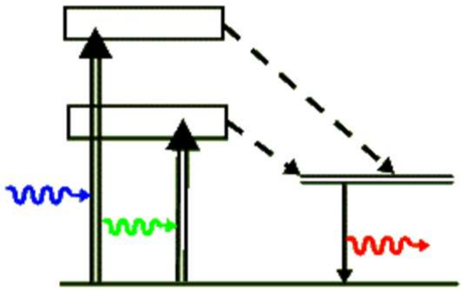
• **Semiconductor lasers,** sometimes called diode lasers, are p-n junctions. Current is the pump source. Applications: laser printers or CD players.

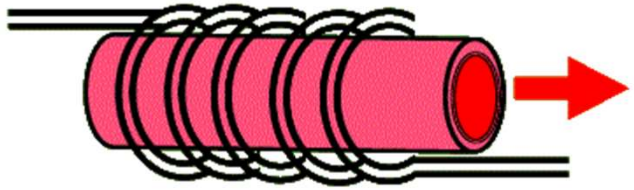
• **Dye lasers** use complex organic dyes, such as rhodamine 6G, in liquid solution or suspension as lasing media. They can be tuned over a broad range of wavelengths.

• **Gas lasers** are pumped by current. Helium-Neon lases in the visible and IR. Argon lases in the visible and UV. CO_2 lasers emit light in the far-infrared (10.6 μm), and are used for cutting hard materials.

• **Excimer Lasers** different reactive gases (e.g. chlorine, fluorine) are used with inert gases (e.g argon, xenon, and krypton). Mixture of these gases is excited- resulting in the formation of excited molecular dimers (excimers).

Solid-state Lasers





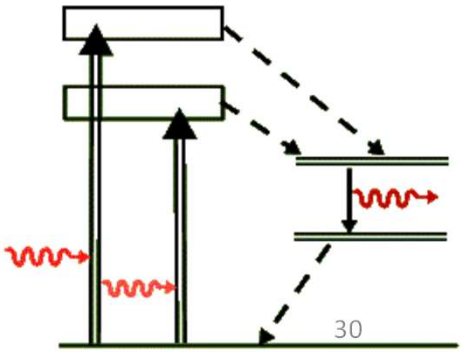
Solid-state Lasers

The first laser ever made, the ruby laser, was a solid-state laser. (atomic transitions of an impurity atom in a crystalline host)
All solid-state lasers are pumped optically. Thus, the host must be transparent to the pumping radiation. Also, the host must be a good heat conductor.
Commonly used solid-state lasers: the Ruby and YAG lasers.

Ruby is an aluminum oxide (Al_2O_3) crystal, called sapphire, with a small amount of chromium oxide (Cr_2O_3) added to it. Sapphire is colorless and transparent, but the chromium doped crystal is pinkish-red in color because it strongly absorbs both in the green and in the blue. When this crystal is excited through the absorption of blue and/or green light (helical flashlamp that surrounds a cylindrical ruby crystal) it soon causes excitation of a meta-stable energy state of the chromium ion (Cr^{+++}). After a typical lifetime of a few milliseconds this state de-excites to the ground state with the emission of a 694.3 nm photon, which is visibly red in color.
Ruby is a 3-level laser and as such it requires high pump energy to achieve population inversion. It can not produce a cw beam but laser pulses.

YAG Lasers

Yttrium-Aluminum-Garnet ($Y_3Al_5O_{12}$), YAG, is a clear and transparent crystal that is most commonly used as the host crystal for neodymium impurity atoms in Nd:YAG lasers. Even though the lasing transition occurs in the Nd ions, these lasers are often called YAG lasers. Typically 1 - 2% of the Y is replaced by Nd in these lasers.

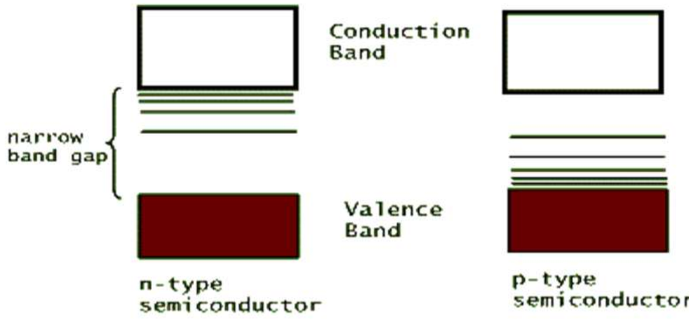


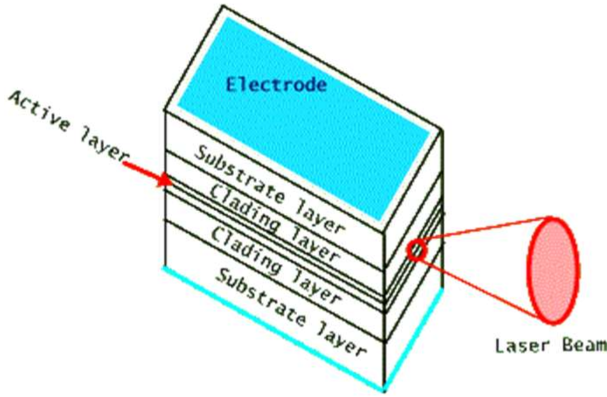
Semiconductor Lasers

Also known as diode-lasers, these are by far the most inexpensive and commonly used lasers in the world.

The first diode-laser was **invented in 1962** at the General Electric Research, New York but only in early 1980's, with the development of innovative semiconductor chip manufacturing techniques, their mass production reached the consumer market.

Similar to their LED cousins, these semiconductor devices generate light from the energy extracted when electron-hole pairs recombine. Also, as in the case of LEDs, the electron-hole pairs in the semiconductor lasers are produced by the flow of electric current in the junction - this is called the injection current. At high injection currents the electron-hole pair density increases to produce population inversion, which leads to lasing. These lasers, in fact, behave very much like LEDs until the critical injection current, called the **threshold current**, is reached.





Semiconductor lasers are **lasers** based on semiconductor **gain media**, where optical gain is usually achieved by **stimulated emission** at an interband transition under conditions of a high carrier density in the conduction band.
The physical origin of gain in a semiconductor (for the usual case of an interband transition) is illustrated in Figure 1. Without pumping, most of the electrons are in the valence band. A pump beam with a **photon** energy slightly above the **band gap energy** can excite electrons into a higher state in the conduction band, from where they quickly decay to states near the bottom of the conduction band. At the same time, the holes generated in the valence band move to the top of the valence band. Electrons in the conduction band can then recombine with these holes, emitting photons with an energy near the bandgap energy. This process can also be **stimulated** by incoming photons with suitable energy. A quantitative description can be based on the Fermi–Dirac distributions for electrons in both bands.
Most semiconductor lasers are **laser diodes**, which are pumped with an electrical current in a region where an n-doped and a p-doped semiconductor material meet. However, there are also **optically pumped** semiconductor lasers, where carriers are generated by absorbed pump light, and **quantum cascade lasers**, where intraband transitions are utilized.

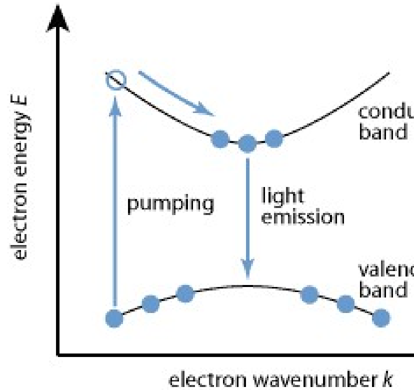


Figure 1: Physical origin of gain in a semiconductor.

Common materials for semiconductor lasers (and for other **optoelectronic** devices) are
- GaAs (gallium arsenide)
- AlGaAs (aluminum gallium arsenide)
- GaP (gallium phosphide)
- InGaP (indium gallium phosphide)
- GaN (gallium nitride)
- InGaAs (indium gallium arsenide)
- GaInNAs (indium gallium arsenide nitride)
- InP (indium phosphide)
- GaInP (gallium indium phosphide)

These are all direct bandgap semiconductors; indirect bandgap semiconductors such as silicon do not exhibit strong and **efficient** light emission. As the **photon** energy of a laser diode is close to the bandgap energy, compositions with different bandgap energies allow for different emission **wavelengths**. For the ternary and quaternary semiconductor compounds, the bandgap energy can be continuously varied in some substantial range. In AlGaAs = $Al_xGa_{1-x}As$, for example, an increased aluminum content (increased x) causes an increase in the bandgap energy.
While the most common semiconductor lasers are operating in the near-**infrared** spectral region, some others generate **red** light (e.g. in GaInP-based **laser pointers**) or **blue** or violet light (with gallium nitrides). For **mid-infrared** emission, there are e.g. lead selenide (PbSe) lasers (*lead salt lasers*) and **quantum cascade lasers**.
Apart from the above-mentioned inorganic semiconductors, organic semiconductor compounds might also be used for semiconductor lasers. The corresponding technology is by far not mature, but its development is pursued because of the attractive prospect of finding a way for cheap mass production of such lasers. So far, only optically pumped organic semiconductor lasers have been demonstrated, whereas for various reasons it is difficult to achieve a high efficiency with electrical pumping.

Semiconductor diode lasers

- A typical diode laser is about a **few hundred microns** in dimension, much smaller than a grain of table salt. its laser light is very divergent and requires the use of a lens to collimate it. Different layers are used to control the confinement of laser light in the active lasing region.
- Diode lasers operate in several modes. Their **wavelength** depends primarily on the size of the band gap of the semiconductor. wavelength outputs from a few microns in the IR all the way to the green in the visible.
- These lasers have a very **high efficiency** and are manufactured to produce laser light from a few mW to several tenths of a Watt.
- They can be made to operate in **cw as well as in a pulsed** mode. Because of their compact size an array of these can be manufactured on single chips, called laser diode arrays, that can generate output powers in the Watt range.
- their output light can be **modulated at very fast rates**. Because of this, and the very narrow band-width light that they can produce, diode lasers have overtaken all other lasers used in the communication industry.

up to a 50-percent electrical-to-optical power conversion rate, at least an order of magnitude larger than most other lasers.

Over the past 20years gradual replacement of other laser types by diode laser based–solutions

Compactness and low power consumption of diode lasers have enabled important new applications (e.g. storing information on compact discs and DVDs, and high-speed, broadband transmission of information via optical fibers).

The semiconductor crystal must be defect free to avoid scattering of carriers and of light.

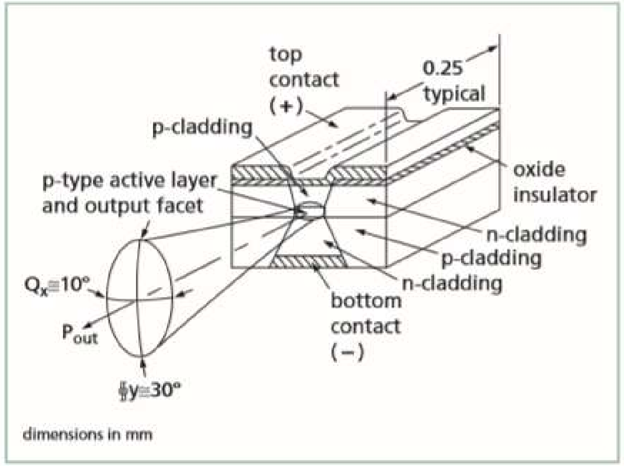


Figure 36.21 **Schematic of a double heterostructure index-guided diode laser**

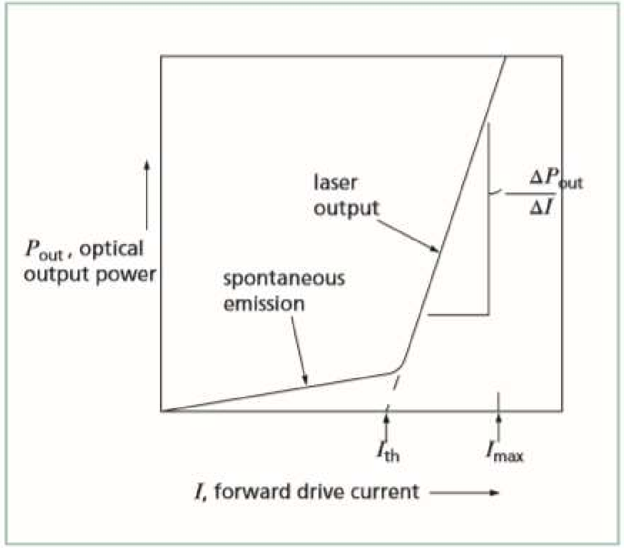


Figure 36.22 **Definition of threshold current, I_{th}, and slope efficiency from the curve of light output, P_{out} vs drive current I**

Semiconductor diode lasers

Gain guiding and index guiding in diode lasers To confine the light laterally (between planes perpendicular to the junction plane), two main methods (with many variants) are used. The first and simplest puts a narrow conductive stripe on the p-side of the device to limit the injected current to a line, giving a gain-guided laser. There is some spreading of current under the stripe, and the light is restricted only by absorption in the unpumped regions of the junction. The transverse mode of the laser light is therefore not tightly controlled. Many high-power diode lasers, used for instance in side-pumping another solid-state laser (where mode control is less critical), are gain guided. More efficient lateral laser mode control is achieved by fabricating, with multiple photolithographic, epitaxial, and etching steps, regions of low index of refraction on either side of the lasing stripe (the two lateral n-cladding regions in the upper half of figure36.21). This confines the light by waveguiding between planes perpendicular to the junction plane as well giving an index-guided laser. These lasers produce a stable single transverse mode of lowest order, as required in data storage applications to read compact discs, and telecommunications applications where coupling into a fiber optic is important.

Threshold current and slope efficiency definitions Output power from a diode laser increases linearly with the drive current excess abovethe threshold current (see figure 36.22). This steeply rising light output curve is extrapolated backward to the zero light output intercept to define the threshold current; the weak incoherent light emission for currents below threshold is due to the spontaneous recombination of carriers such as occurs in LEDs. When divided by the drive voltage V, the slope of the output vs current curve yields the differential (above threshold) electrical-to-optical power conversion efficiency (also termed the slope or quantum efficiency) which ranges from 50 to 80 percent for various devices.

DIODE-PUMPED SOLID STATE LASERS

The "DPSS laser revolution": The optical difficulties encountered with diode lasers—difficulty in coupling due to the high divergent light, poor mode quality in the slow axis of wide-stripe lasers, low output power from single-transverse-mode lasers— led to a new philosophy about how best to use these efficient, long-lived, compact light sources (1980s, Stanford University, Prof. Bob Byer)

The primary light source (the diode laser) pumps another laser (an infrared crystal laser) to convert to a good mode, the beam of which is wavelength converted (by nonlinear optics techniques) to a visible output. **The diode laser source replaces the discharge lamp.**

Though power is lost at each step, the result is still a single-mode visible beam generated with a total electrical-to-optical conversion efficiency of several percent. These DPSS lasers are replacing the older visible gas lasers whose conversion efficiencies rarely reach 0.1 percent.

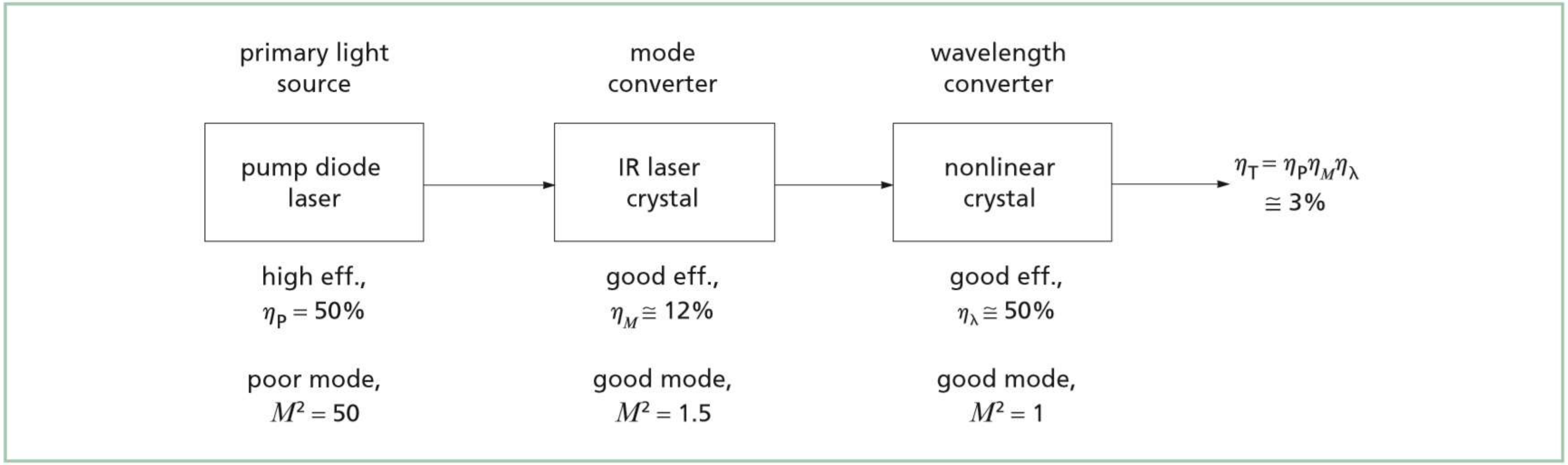
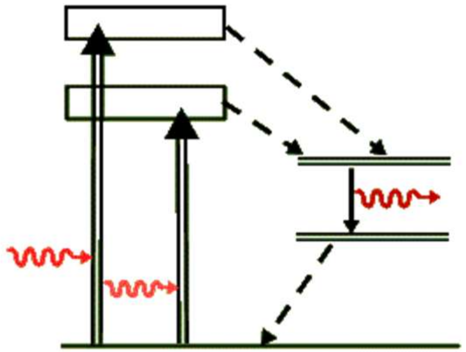


Figure 36.26 **The logic for DPSS lasers**

YAG Lasers

Yttrium-Aluminum-Garnet ($Y_3Al_5O_{12}$), YAG, is a clear and transparent crystal that is most commonly used as the host crystal for neodymium impurity atoms in Nd:YAG lasers. Even though the lasing transition occurs in the Nd ions, these lasers are often called YAG lasers. Typically 1 - 2% of the Y is replaced by Nd in these lasers. Similar to the ruby laser, here again the crystal not only hosts the atom, but also its broad absorption bands (in the presence of the Nd-impurity) effectively absorb optical radiation - mostly around 700 nm and 800 nm. This energy is then transferred to the impurity ions through non-radiative processes.



Similar to the level diagram for the ruby laser, the above diagram is a simplified representation of the transitions for the neodymium ion, Nd^{+++}, that take place in the YAG laser. Again, the dashed arrows indicate non-radiative transitions, where the energy lost in them is transferred as heat to the crystal. But unlike the ruby laser, the Nd:YAG is a four-level laser and has much more efficient lasing transitions than the ruby laser. Because of this efficiency in population inversion it can be pumped to produce a wide variety of laser output energies and can be operated in the cw as well as pulsed modes. The lasing photon has a wavelength of 1064 nm, well in the IR range.

Another host used for Nd is plain glass, but its optical and thermal properties are not as desirable as YAG's. The trade off is that growing large YAG crystals is not easy. A typical YAG rod, which is drilled out of a crystal block, is smaller than 1 cm in diameter and from a few to 10 cm in length. Still, these lasers can produce high output powers by using several rods in tandem. Pulsed YAG lasers can produce high peak powers by Q-switching and/or by using several rods as amplifiers. When used as amplifiers, the rods are not coated for reflectivity to produce optical amplification in the rod. Instead, the output of the first rod (the oscillator) is used as a Q-switch to generate stimulated emission in the next rod (the amplifier), and so on.

In the cw mode YAG lasers are pumped either by an arc lamp or a semiconductor laser. Pumping with a diode laser is more efficient because the diode's wavelength can be chosen to closely match the absorption of the YAG. Flashlamps are often used for pulsed operation of these lasers. In this mode Q-switching the laser can produce ns pulses with relatively high peak powers. But, to reach very high powers, like that generated by the NOVA laser, many rod amplifications are necessary. Link to NOVA Web Page

YAG lasers are extremely versatile. They are used in applications from welding and drilling to range finding. Because their output wavelength is not visible, YAG lasers are used in many applications that require secrecy; from military to security applications. It is now possible to convert IR radiation into the visible range using so called non-linear crystals (also known as second-harmonic-

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Pakistan
Lasers, Q-switching and mode-locking

The Abdus Salam
International Centre for Theoretical Physics

Medical Applications of Lasers

The various interactions of laser light of different wavelengths with body tissue give rise to a myriad of medical applications. One fundamental interaction is simply the **heating of tissue** through the absorption of light. At elevated temperatures proteins will denature or coagulate just as an egg does when cooked. **Laser-induced denaturation is known as photocoagulation** and is of primary importance in laser surgery.

Infrared light is very strongly absorbed by water. Photocoagulation is used in surgery for the destruction of tumors, retinal surgery and in many internal surgeries using fiber optics to gain internal access without having to open up the body.

A major advantage of laser surgery is the fact that small blood vessels are **cauterized**, with a large reduction in bleeding.

Furthermore, high photon powers in short pulses can deliver large doses of energy to actually vaporize tissue locally, in a process known as **photovaporization**. Such high energy doses raise the local temperature above the boiling point of water for long enough to completely vaporize the tissue, resulting in clean cuts with no bleeding and very limited damage to neighboring tissue. Usually this results in less pain and swelling (edema) and a more rapid recovery from surgery. Laser surgery is particularly effective in areas of the body that are full of blood vessels and prone to much bleeding.

The **wavelength** of laser light, and therefore the type of laser, used will depend on the tissue to be destroyed. Strong absorption lines are used to ensure specific destruction of that type of tissue; for example, blood rich tissue will absorb strongly at a wavelength of 575 nm due to a strong hemoglobin absorption line. Similarly, in retinal surgery, the lens of the eye is transparent to visible light, so that visible light can be used to surgically seal leaky capillaries behind the retina or to re-attach a retina by spot-welding using coagulated blood. Until this type of laser surgery was available, a detached retina was a leading cause of blindness.

Early laser surgery used a **carbon dioxide** laser because of its intense IR beam, but fiber optics do not work so well at the 10 mm wavelength and a more cumbersome mirrored articulated tool was used. Note that the IR beam is invisible and so the surgeon could not see where the beam is without the use of a **low-powered co-linear He-Ne laser**. The laser of choice for visible light has been the argon ion laser with its intense blue/green beam. **Excimer lasers** are increasingly being used since their high energy uv pulses have enough energy to photodecompose tissue, essentially vaporizing it without any spread of heat to neighboring tissue.

Medical Applications of Lasers

removing birthmarks, tatoos, port-wine stains, warts, etc.

laser acupuncture - flooding nerve endings with laser light instead of using needles

laser **lithotripsy** - A high powered laser to used to break up kidney stones or gallstones, mineral deposits that will not pass through ducts. Stones can lead to painful incidents if they clog a duct. One treatment uses lasers while a second, probably more common treatment uses focused ultrasonic (shock) waves to also break up stones.

laser **angioplasty** - Plaque is the buildup of fatty deposits on the arterial walls and it can lead to a blockage or heart problems from excess strain in pumping blood. Laser light can be used, via insertion in a fiber optic catheter, to drill a hole in the plaque and clear a blockage. Most often laser angioplasty is done in conjunction with balloon angioplasty which insures that the arterial wall stays open. Also, often a stent, or wire mesh cylinder, is inserted to prevent the arterial wall from collapsing, although plaque sometimes tends to re-collect on the stent or near damaged scar tissue. See this web site for more information: laser angioplasty

photodynamic therapy - Certain types of chemicals, known as photosensitizing agents, are able to bind to cells and then kill them when they are exposed to light of a particular wavelength. In treating cancer, these agents are injected into the blood stream and, after waiting an appropriate length of time for them to leave normal cells but still be present in malignant cells, light is directed on the tumors using a fiber-optic catheter. The tumors must be on or near the surface of skin or the lining of internal organs so that the laser light can penetrate the full extent of the tumor. The interaction with the light produces free radicals, very active chemical groups that oxidize tissue, killing it. See: photodynamic therapy

lasik eye surgery- A laser beam is used to re-sculpt (flatten) the surface of the cornea in order to correct for myopia (nearsightedness) or make a series of cuts in the cornea to cause it to bulge more in order to correct for hyperopia (far-sightedness). This procedure is becoming very common and has a high success rate. Nearsighted people over about 40 years of age also have presbyopia, or blurry near vision with normal eyeglasses due to a stiffening of the lens with age. Normally these people would wear bi-focals, allowing for good distance and reading vision. In one variation of LASIK, one eye is left alone so that the person would have good near vision without glasses, while the other eye is treated to produce good distance vision. Roughly 75% of people who have had this surgery are able to adjust to seeing independently with their eyes, while the others get LASIK on the other eye and will need to wear reading glasses for close vision. See LASIK

Tunable Operation

Many lasers can operate at more than one wavelength. Argon and krypton lasers can operate at discrete wavelengths ranging from the ultraviolet to the near infrared. Dye lasers can be continuously tuned over a spectrum of wavelengths determined by the fluorescence bandwidths of the specific dyes (typically about 150 nm). Alexandrite and titanium sapphire lasers can be tuned continuously over specific spectral regions. To create a tunable laser, the cavity coatings must be sufficiently broadband to accommodate the entire tuning range, and a variable-wavelength tuning element must be introduced into the cavity, either between th cavity optics or replacing the high-reflecting optic, to introduce loss at undesired wavelengths. Three tuning mechanisms are in general use: Littrow prisms, diffraction gratings, and birefringent filters. Littrow prisms (see figure 36.16) and their close relative, th full-dispersing prism, are used extensively with gas lasers that operate at discrete wavelengths. In its simplest form, the Littrow prism is a 30-60-90-degree prism with the surface opposite the 60-degree angle coated with a broadband high-reflecting coating. The prism is oriented so that the desired wavelength is reflected back along the optical axis, and the other wavelengths are dispersed off axis. By rotating the prism the retroreflected wavelength can be changed. In laser applications, the prism replaces the high-reflecting mirror, and the prism's anglesarealtered (typically to 34, 56, and 90 degrees) to minimize intracavity losses by having the beam enter the prism exactly at Brewster's angle. For highe power lasers which require greater dispersion to separate closely spaced lines, the Littrow prism can be replaced by a full-dispersing prism coupled with a high reflecting mirror. Gratings are used for laser systems that require a higher degree of dispersion than that of a full-dispersing prism.   Birefringent filters have come into general use for continuously tunable dye and Ti:Sapphire lasers, since they introduce significantly lower loss than do gratings. The filter is made from a thin, crystalline-quartz plate with its fast axis oriented in the plane of the plate. The filter, placed at Brewster's angle in the laser beam, acts like a weak etalon with a free spectral range wider than the gain curve of the lasing medium. Rotating the filter around the normal to its face shifts the transmission bands, tuning the laser. Since there are no coatings and the filter is at Brewster's angle (thereby polarizing the laser), there are no inherent cavity reflection losses at the peak of the transmission band. A single filter does not have as significant a line-narrowing effect as does a grating, but this ca be overcome by stacking multiple filter plates together, with each successive plate having a smaller free spectral range.

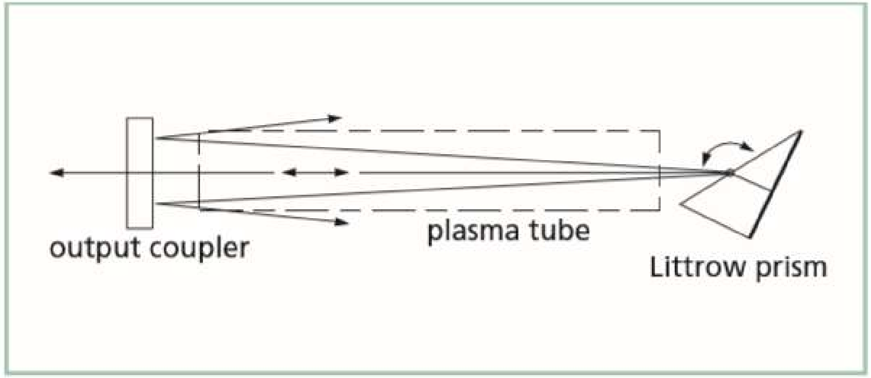
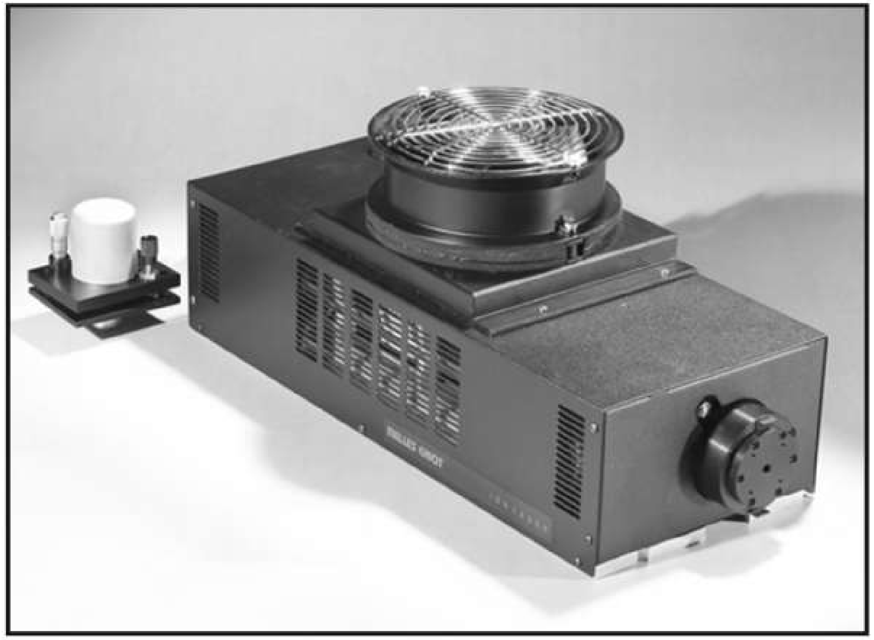


Figure 36.16 **Littrow prism used to select a single wavelength**



Prism-tunable-ion laser

Spectral Regions Covered by Laser Emissions

Using different active media with very different emission spectra, it has been possible to assemble lasers working in different spectral regions.

1 - Ultraviolet : nitrogen (N_2) laser, exciplex lasers.

2 - Visible : Ar^+, Kr^+, He-Ne, ruby, organic dye, semiconductor lasers.

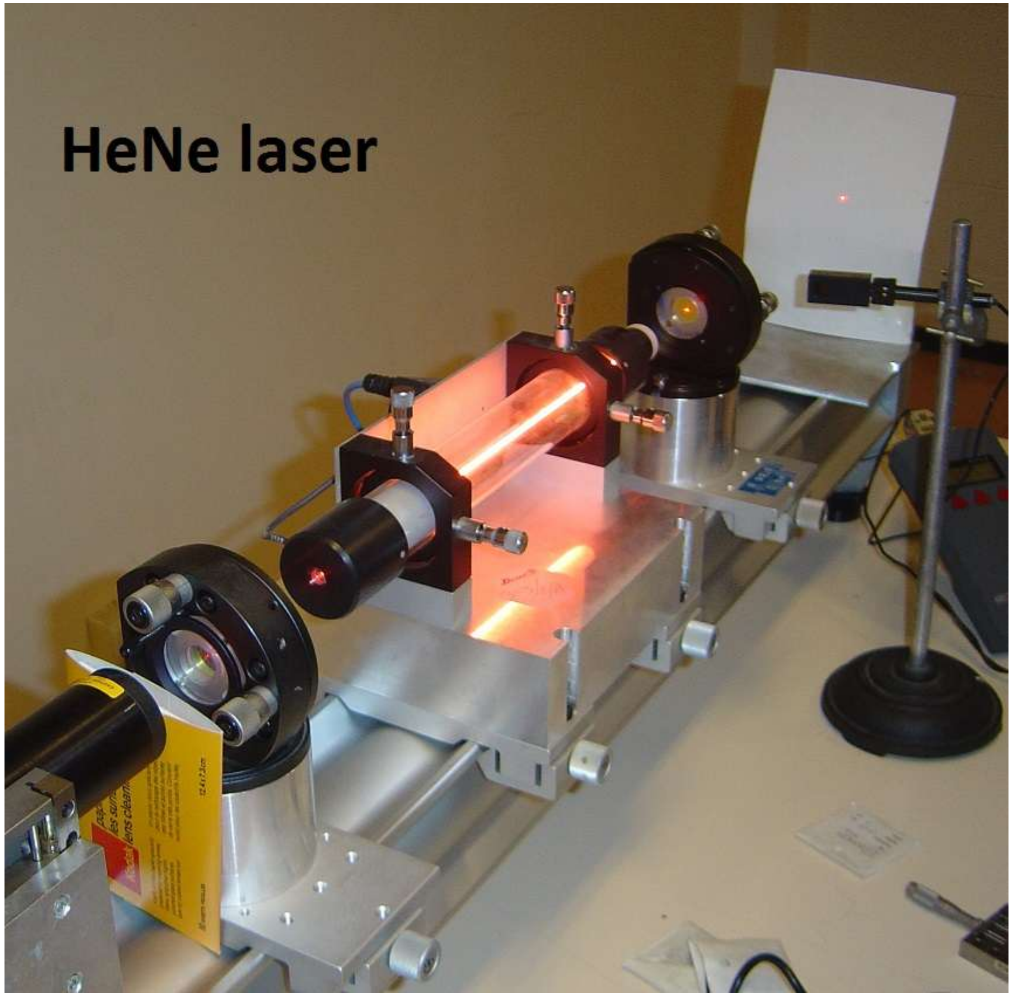
3 - NearInfraRed : Nd:YAG, titanium-sapphire, semiconductor lasers.

4 - MidInfraRed : CO_2 , HF, semiconductor lasers.

Using suitable nonlinear crystals, it is possible to generate harmonics ($2\nu_0$, $3\nu_0$) of the fundamental emission frequency ν_0 , so that an expanded spectral range can be obtained.

Nd:YAG laser : 1064 nm (NIR) $\rightarrow$ x2 = 532 nm (VIS) $\rightarrow$ x3 = 355 nm (UV)

Monoatomic Gas Lasers



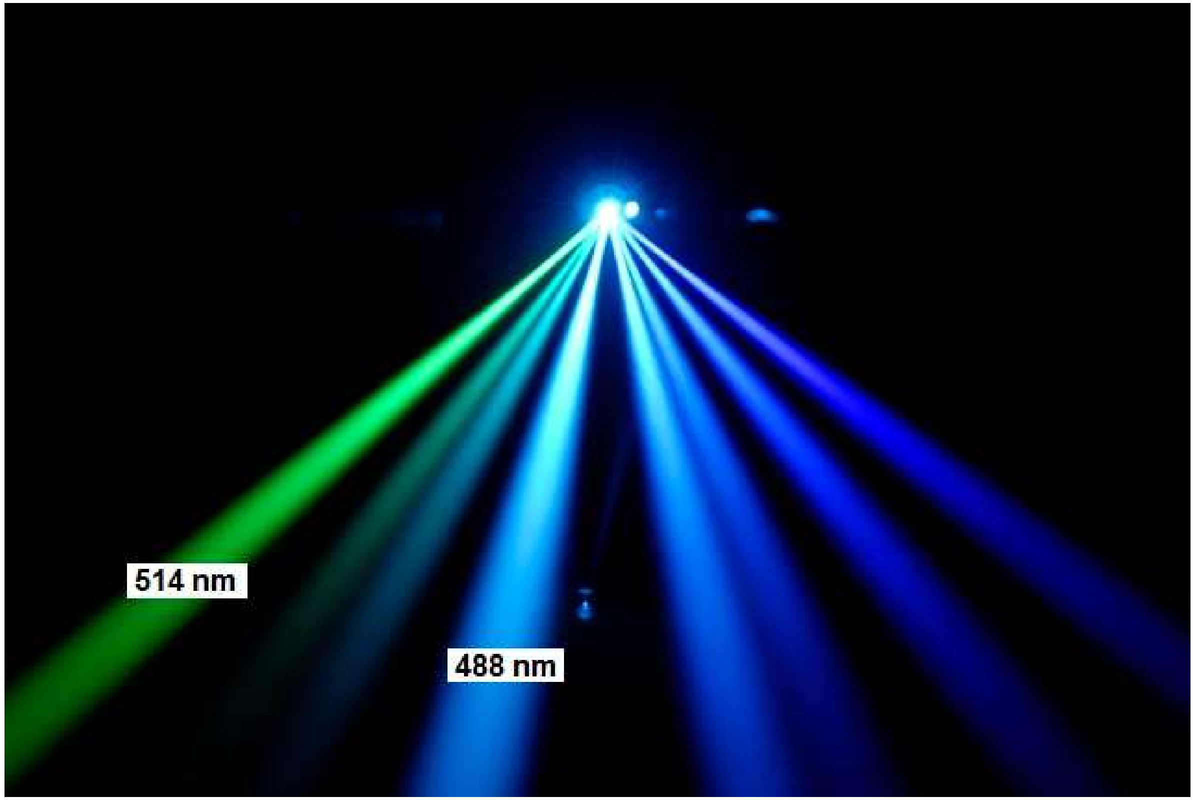
They are based on emissions of neutral or ionized atoms in the gas phase. Excitation is produced by electron impact (electric discharge). The most important are :

1 – He-Ne laser. Red emission at 632.8 nm (Ne line). Low-power cw laser (≈ 10 mW). It is the best approximation of the "ideal" laser. Metrological applications.

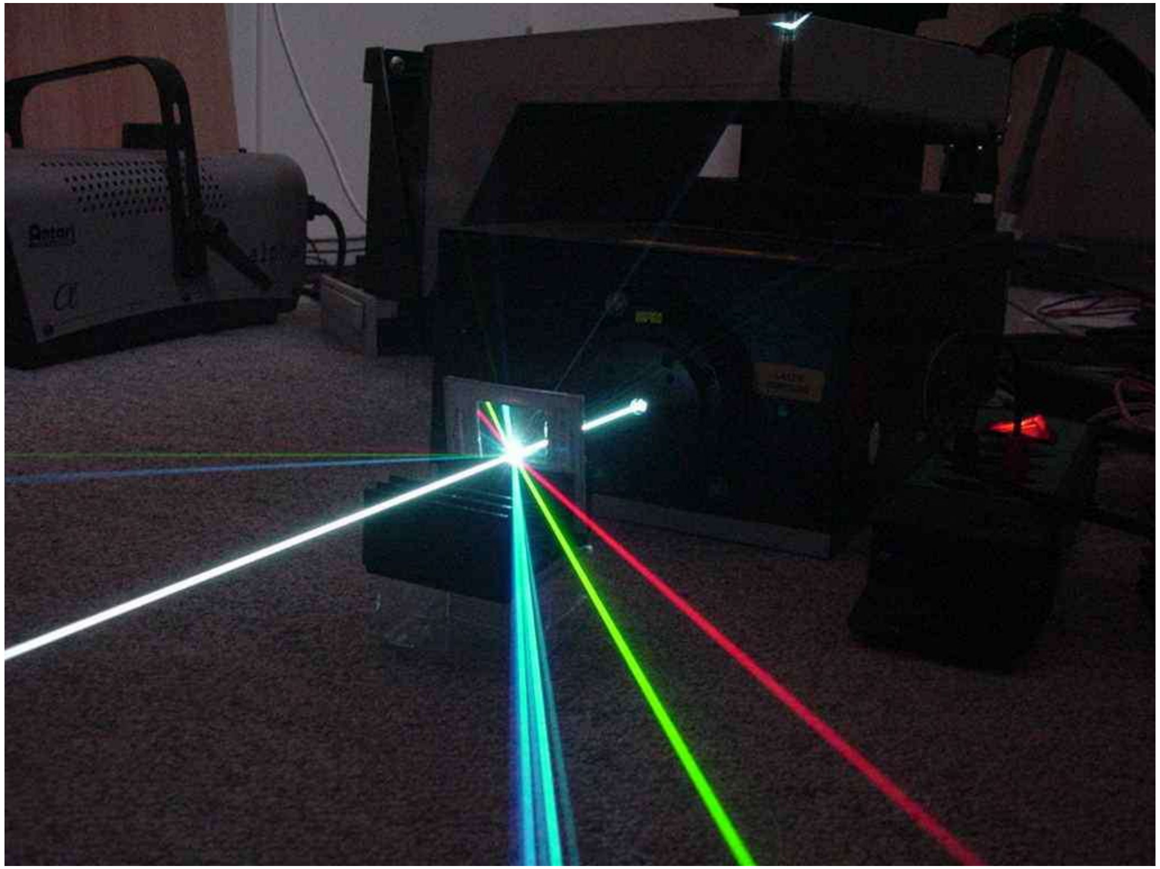
2 – Ar^+ laser. Many laser lines in the blue-green region. Medium-power cw laser (≈ 10 W at 514.5 nm). Used for Raman spectroscopy, optical pumping of solid-state and dye lasers, confocal microscopy, and for the treatment of some retinopathies.

3 - Kr^+ laser. It is similar to the Ar^+ laser, but the more intense emission is red (647.1 nm, ≈ 3 W). Krypton and Argon can be mixed in the same laser, thus creating a "white-light" laser with many monochromatic lines available in the visible region.

Ar^+ Laser



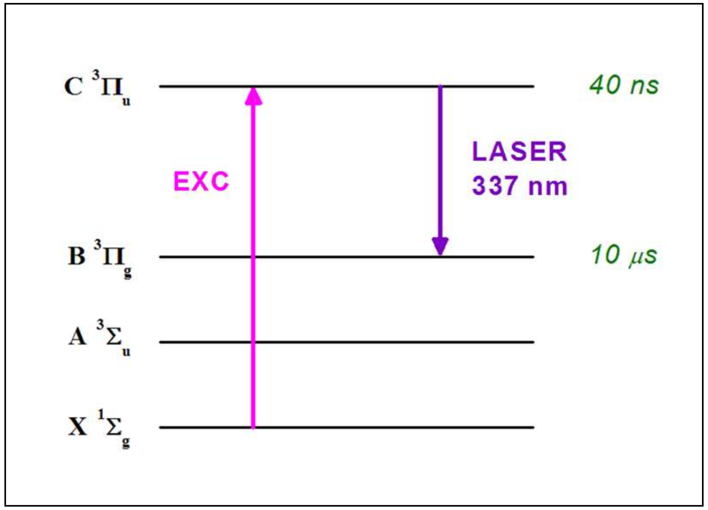
white-light Laser (Ar^+ and Kr^+)



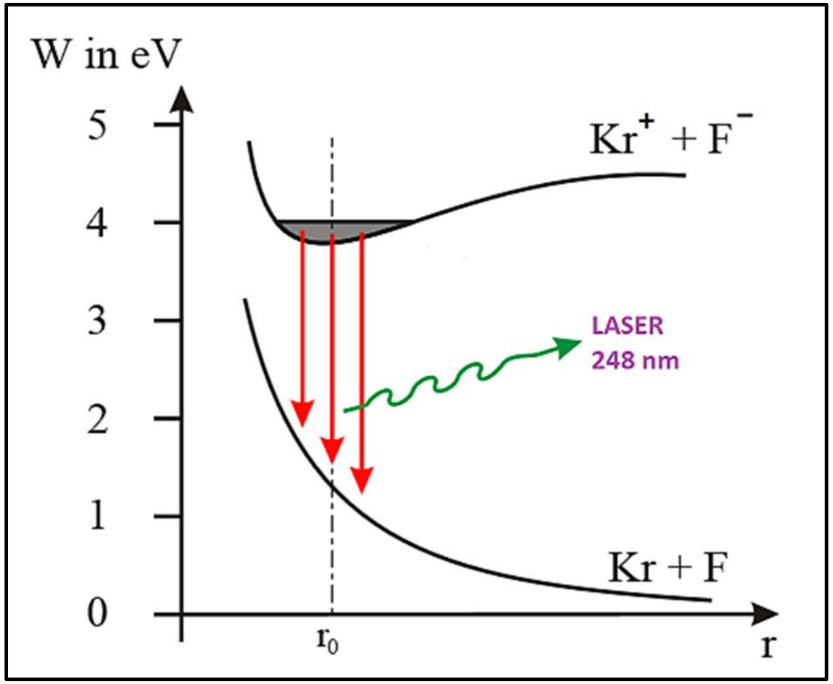
Molecular Gas Lasers

The active medium is made of molecules in the gas phase. Excitation is produced by electron impact (electric discharge). The most important are :

1 - nitrogen (N_2) laser. It is the most common UV laser ($C\,^3\Pi_u \rightarrow B\,^3\Pi_g$ transition, 337 nm). It is a powerful pulsed laser (≈ 1 MegaW of peak power), frequently used for the optical pumping of dye lasers, and in the MALDI-TOF mass spectrometers.



2 – exciplex lasers. The active medium is an electronically excited diatomic complex (exciplex), in which a halogen atom (F, Cl) is bound to a noble gas atom (Ar, Kr, Xe). Since the electronic ground state is repulsive, the radiative decay to the ground state is immediately followed by dissociation.



Exciplexes are produced "in situ" by means of a pulsed electric discharge in a gaseous mixture in which halogen molecules and noble gas atoms are diluted in helium.

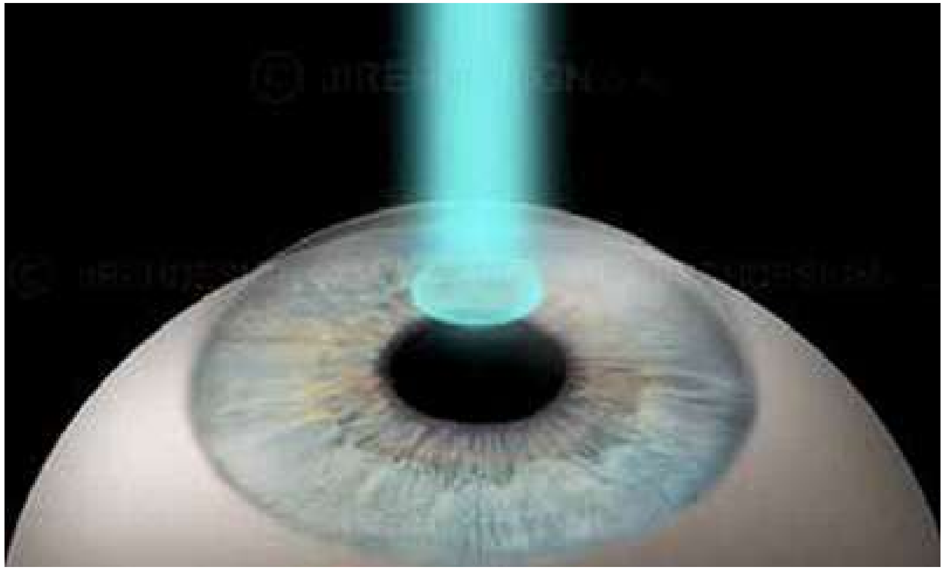
$Kr \xrightarrow{\text{discharge}} Kr^+$	*(ionization)*
$F_2 \xrightarrow{\text{discharge}} F^- + F$	*(dissociative attachment)*
$Kr^+ + F^- + He \rightarrow KrF^*$	*(exciplex formation)*
$KrF^* \rightarrow KrF + h\nu$	*(UV emission)*
$KrF \rightarrow Kr + F$	*(complex dissociation)*
$F + F \rightarrow F_2$	*(molecular halogen regeneration)*

Population inversion is assured by the fact that the final level of the lasing transition is always empty. The various exciplexes emit in the UV region, giving laser lines between 193 and 351 nm.

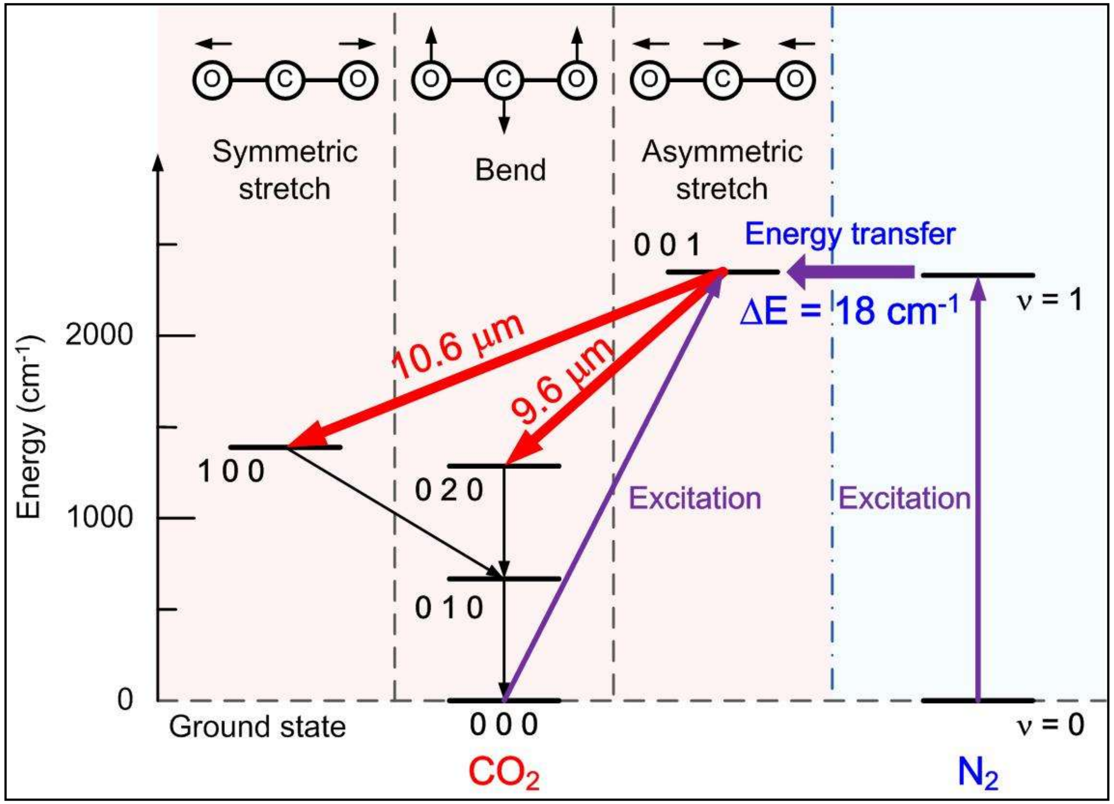
Large pulsed power (MegaW range) and good optical quality of the beam.

Suitable for precision micromachining of both hard and soft materials, which are vaporized without thermal effects (laser ablation).

Micro-photolithography and corneal sculpting to correct myopia are among the main applications.

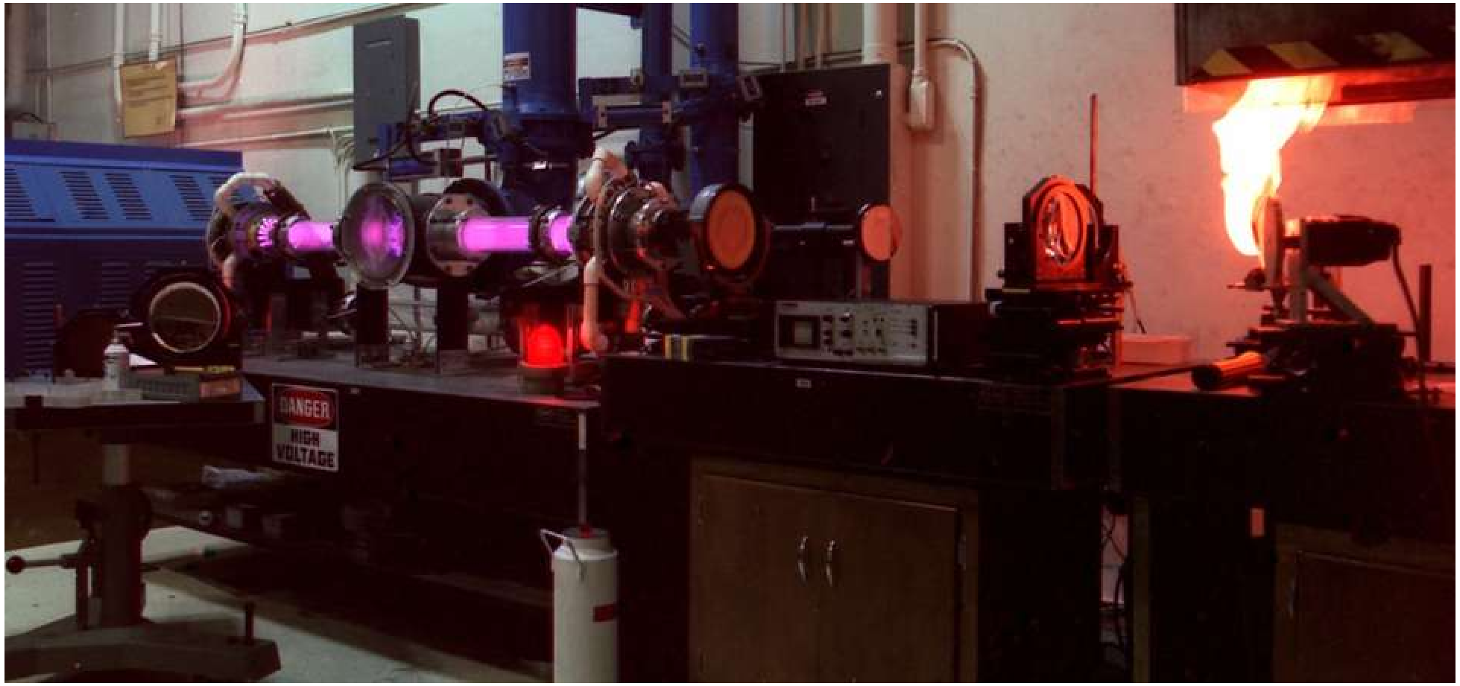


3 – CO_2 laser. The active medium is made of a gaseous mixture CO_2 / N_2 / He. An electric discharge produces population inversion between vibrational excited states of CO_2 .

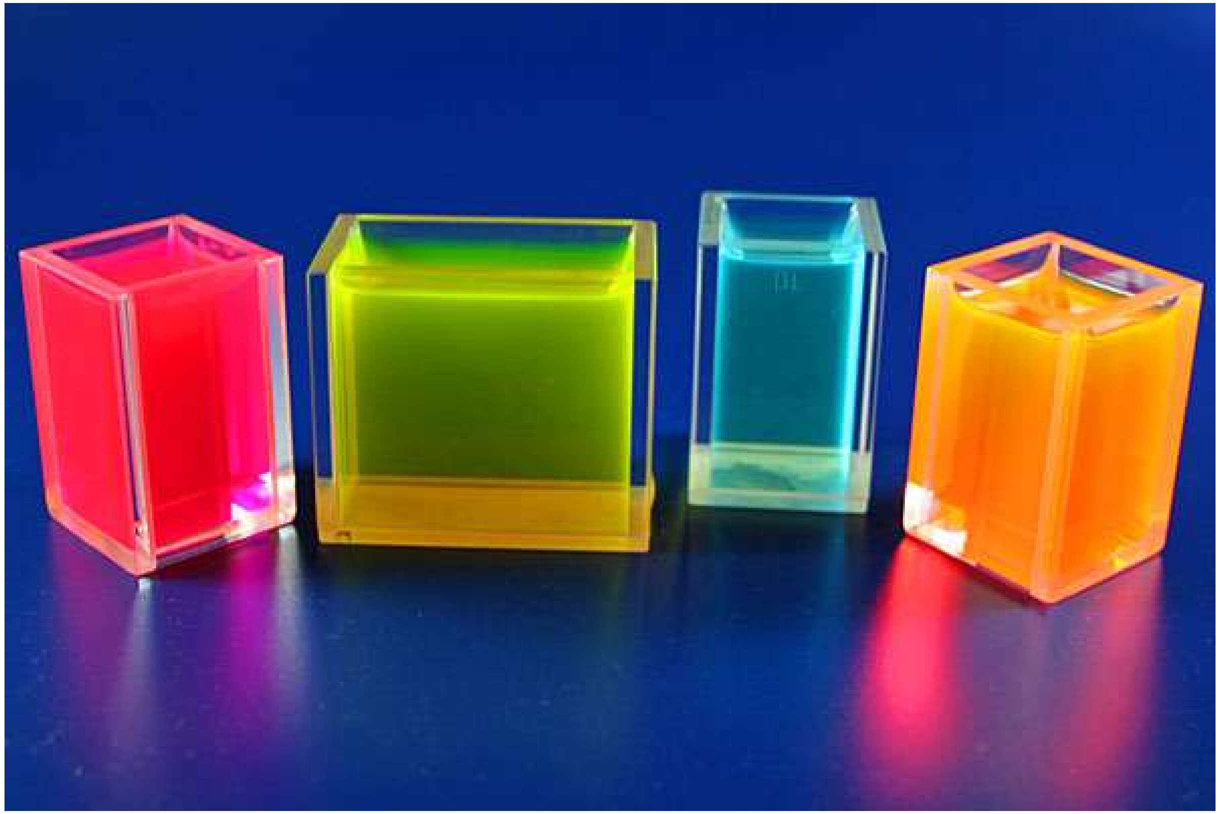


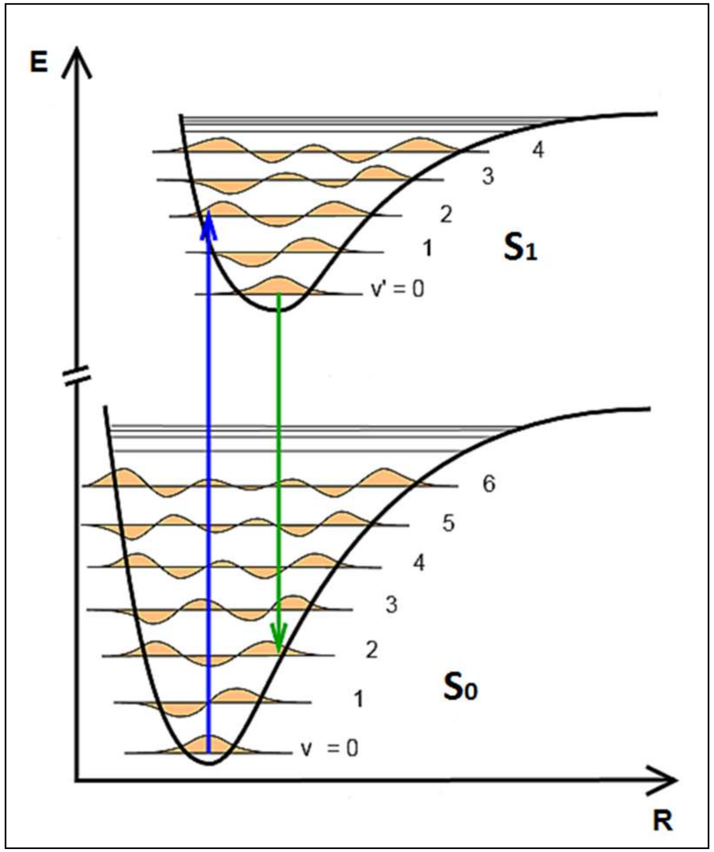
The CO_2 laser emits in the mid-IR near 1000 cm^{-1}. The laser emission consist of two ro-vibrational bands which include tens of narrow rotational components. It is a very efficient and powerful laser (kW level in cw). The first laser largely used for industrial applications (cutting, welding, engraving, sintering etc.).

Research applications for high-resolution IR spectroscopy (laser-stark, microwave-IR side-band spectroscopy), and for the study of laser-induced reactions by vibrational excitation of the reactants.
Widely used also for laser surgery : both cutting of soft tissue and haemostasis are achieved photo-thermally.



Dye Lasers





Dye lasers are 4-level vibronic molecular lasers, in which the active medium is a solution containing a strongly photoluminescent organic dye.

Optical pumping is employed, using flash-lamps or powerful lasers emitting in the VIS or UV regions.

Many different dyes can be used, so that laser emissions in the whole visible range can be obtained.

Low-medium power.

Dye lasers have very large emission bands, therefore:

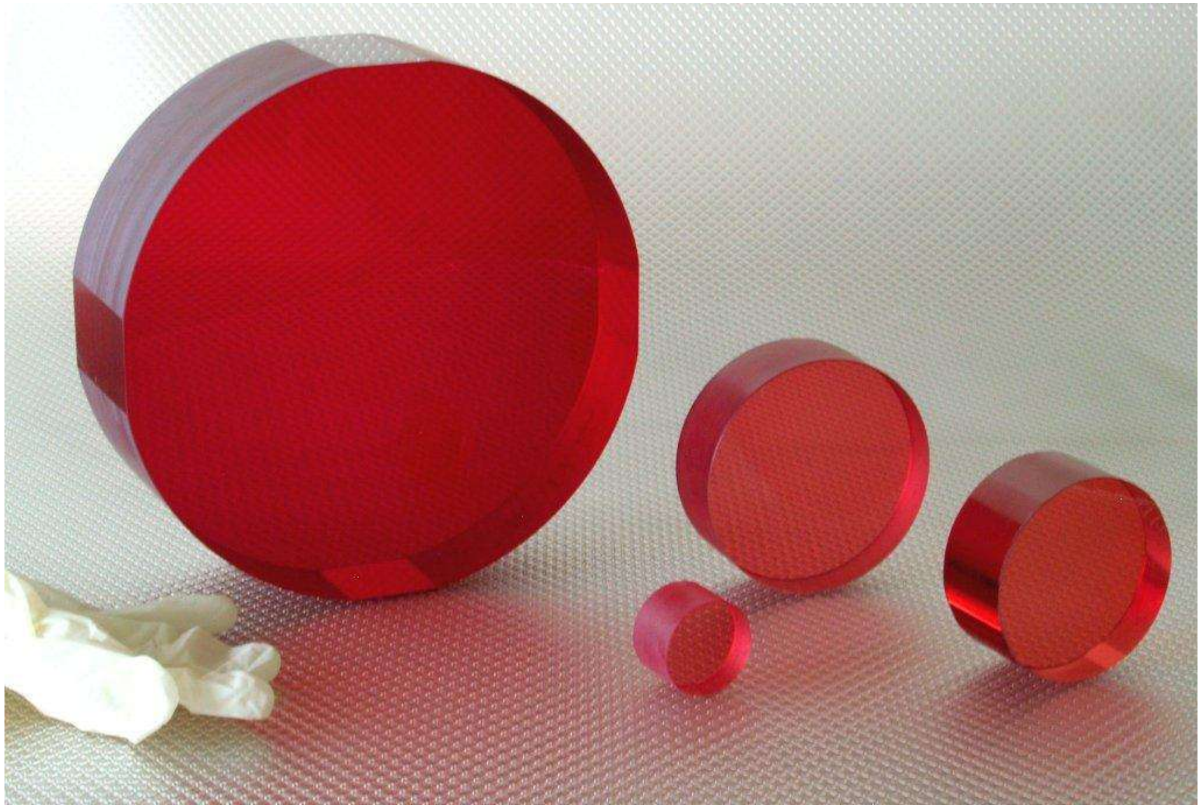
1 – they are tunable lasers, that means that the emission wavelength can be varied continuously along the profile of the fluorescence band. High resolution spectroscopy in the visible region is possible.

2 – ultrashort pulses can be created using the mode-locking technique. Theory predicts that the pulse duration Δτ depends on the width of the emission band in the following way:

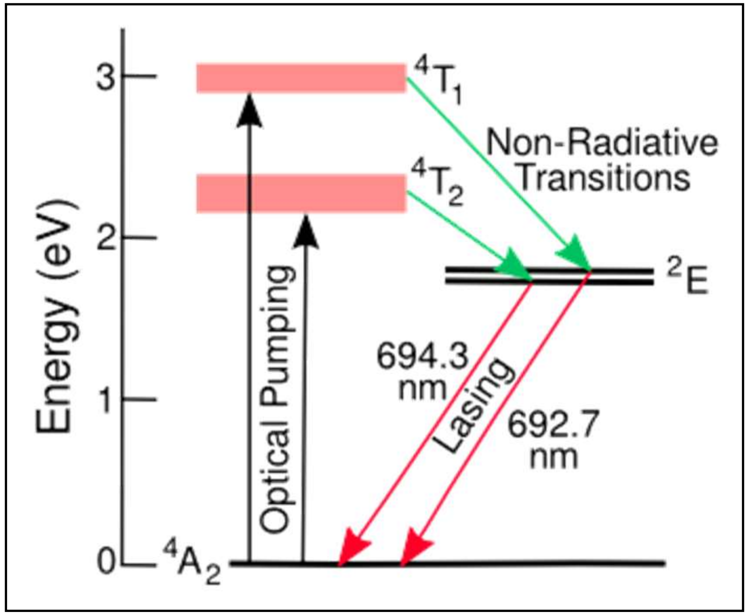
$$\Delta\tau = \frac{1}{\Delta\nu_{band}}$$

For example, a dye laser with an emission band from 475 to 525 nm can generate pulses having a duration of 17 fs.
Ultrashort pulses allowed for the birth of femtochemistry.
(Transition State Spectroscopy, Nobel Prize to Ahmed Zewail in 1999).

Crystalline Lasers



The active medium is a crystalline material made of a passive host doped with an activator which provides the photophysical properties (absorption / emission) useful to obtain laser action. Optical pumping is always used (flash lamps or laser sources) .

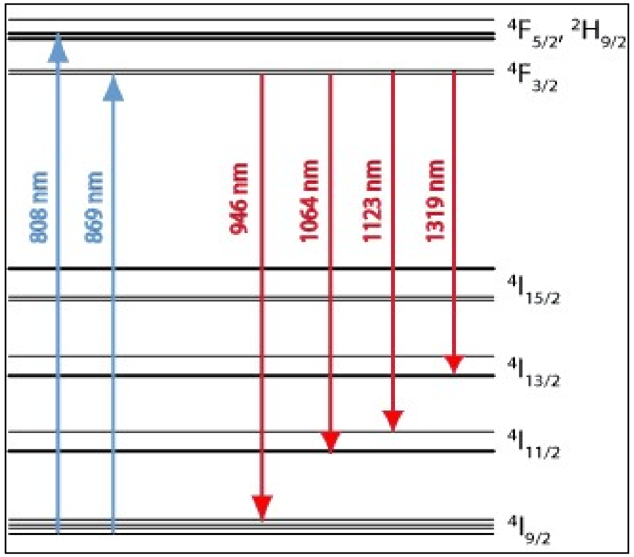


Ruby Laser

The first type of laser made to operate (1960).

Host is colourless corundum (Al_2O_3) , activator is the Cr^{3+} ion, which makes the crystal red.

It is a pulsed, self-terminating laser with a powerful emission at 694.3 nm (red). Optically pumped using a white-light flash lamp.



Nd:YAG Laser. Host is YAG (Yttrium Aluminium Garnet, $Y_3Al_5O_{24}$), activator is the Nd^{3+} ion. Optically pumped by a flash lamp or by a semiconductor laser at 808 nm. It is a very powerful cw laser which emits in the NIR region. The main emission is at 1064 nm (= 9398 cm^{-1}).

Further laser emissions can be obtained in the NIR region. The initial state is always $^4F_{3/2}$ (τ = 230 μS) which emits toward the four spin-orbit levels of the ^4I_J electronic ground state of Nd^{3+}. In addition to YAG other hosts can be used: $YLiF_4$, YVO_4, but also glasses based on P_2O_5 (Nd:glass laser). Using different hosts and NIR emissions, a large variety of neodymium based lasers can be manufactured.

A Nd:YAG laser emitting at 1064 nm is an extremely powerful source (hundreds of Watt in cw), so that it can replace the CO_2 laser for machining of materials. This power can be greatly increased in the pulsed regime using the Q-switching technique, so that peak powers near 1 GigaW (=10^9 W) can be produced. Peak powers at the TeraW level (=10^{12} W) have been obtained using huge Nd:glass lasers.

The frequencies of NIR emissions can be very efficiently doubled, thus obtaining laser sources which emit in the visible region (several W cw):

1064 nm (Nd:YAG) ► 532 nm (green)

946 nm (Nd:YAG) ► 473 nm (blue)

1342 nm (Nd:YVO_4) ► 671 nm (red)

Starting from 1064 nm, it is possible to generate also the 3rd and 4th harmonics (355 and 266 nm respectively), thus obtaining UV laser sources.

A doubled Nd:YAG laser (532nm, 100 mW cw) used to record the Raman spectrum of a quartz crystal (Physical-Chemistry Students' Lab).

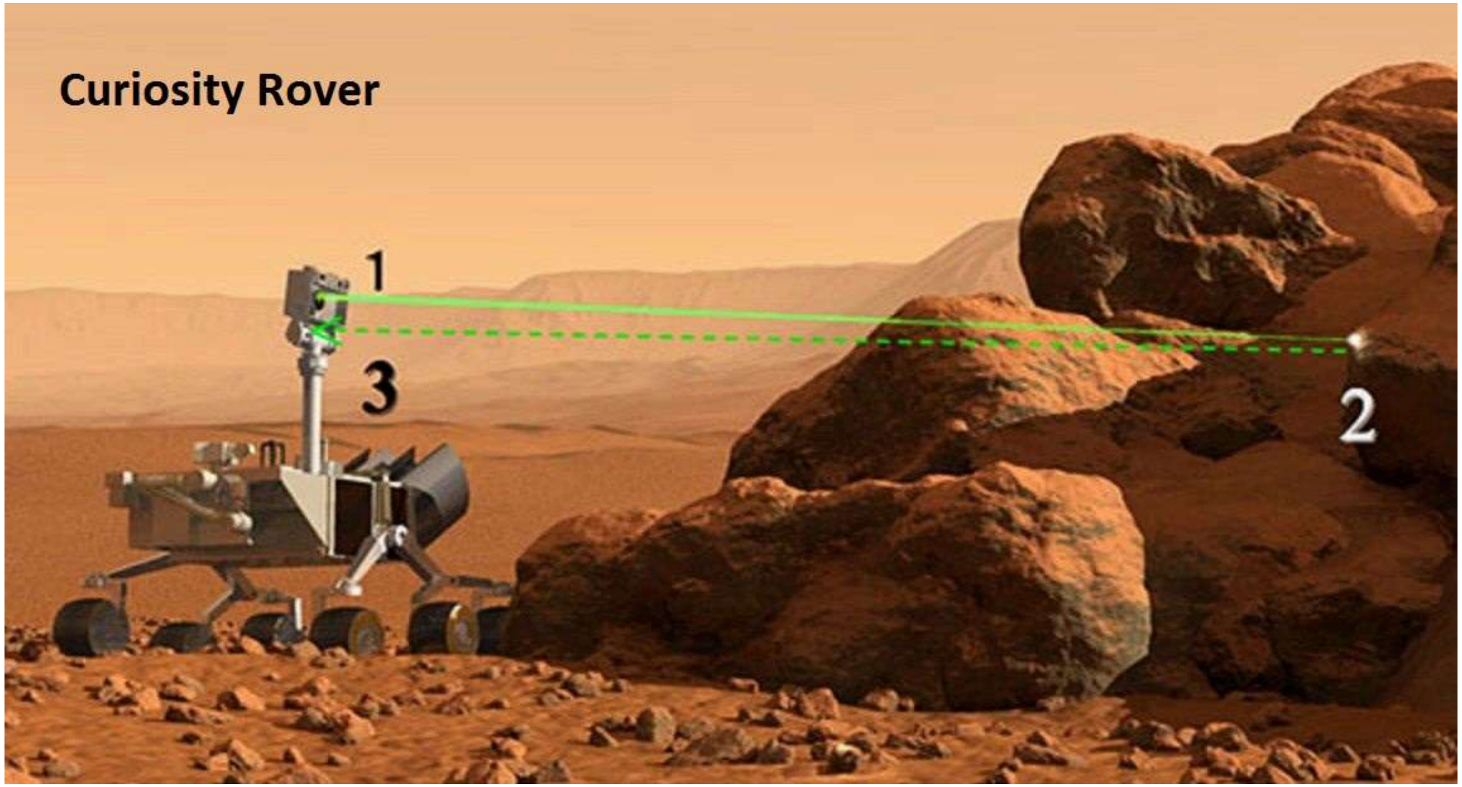
Since a neodymium laser can be also pumped by a small semiconductor laser, which is powered by normal batteries, portable neodymiun lasers can be also manufactured (green pointers).

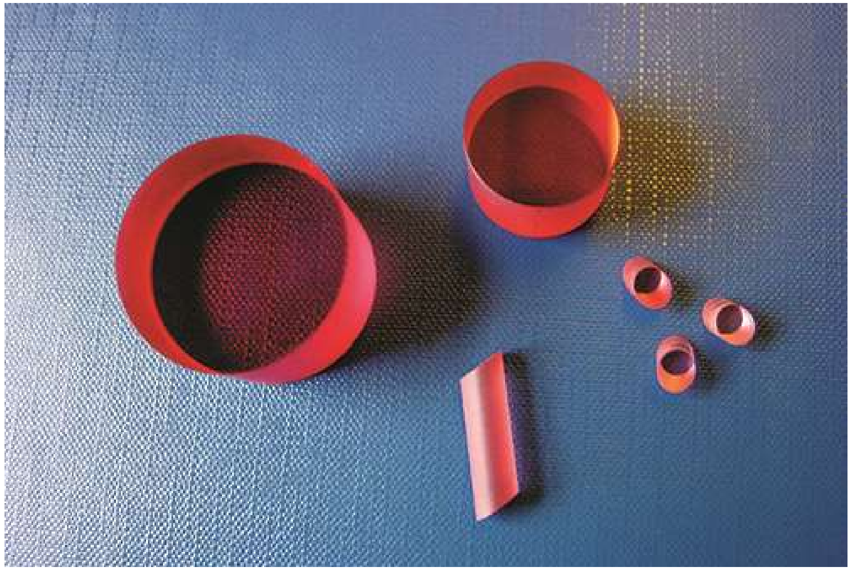
a very unportable Nd:glass Laser

a Nd:KGW laser is on Mars since 2012

it shoots 10 MegaWatt pulses at the rocks (1), a spark is produced (2), and atomic emission spectra are recorded (3)

(Laser Induced Breakdown Spectroscopy technique)

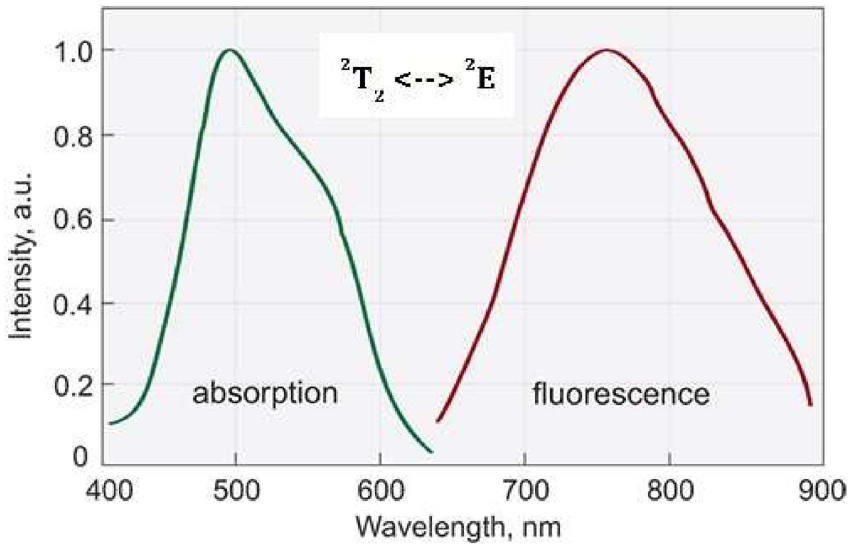




Titanium Sapphire Laser

Host is corundum (Al_2O_3), activator is the Ti^{3+} ion. This crystalline material has a large absorption band peaked at 488 nm, and an equally large emission band peaked at 795 nm.

It is optically pumped using a flash-lamp or lasers emitting in the blue/green regions (Ar^+ or doubled Nd:YAG).
It is a cw laser of medium power (a few W) .



The Ti:sapphire laser is very similar to a dye laser. It is the 4-level vibronic laser with the largest emission band (from red to NIR), and it is therefore tunable over a wide spectral range. The most important application is generating femtosecond laser pulses, useful for studies in which a very high temporal resolution is needed.

Laser: Medical Applications

- **Cosmetic surgery:** removing tattoos, scars, stretch marks, wrinkles, birthmarks, and hairs.
- **Dentistry:** caries removal, tooth whitening, and oral surgery.
- **Dermatology:** Treatment of acne and skin cancer by PDT
- **Eye surgery:** Cataract and Glaucoma surgery
- **Cardiology:** Angioplasty, vessel recanalization
- **Neurology:** To cut, ,vaporize and coagulate tissue with out mechanical contacts
- **Urology:** lithotripsy (removal of kidney stones)
- **Laser scalpel:** gynecology, urology, laparoscopy
- **Optical Imaging:** field of online monitoring and diagnostics

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- LASERS: Peter W, Milonni and Joseph H. Eberly
- LASERS : Anthony E. Siegman
- LASER FUNDAMENTALS: William T. Silfvast

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Lasers, Q-switching and mode-locking

The Abdus Salam International Centre for Theoretical Physics