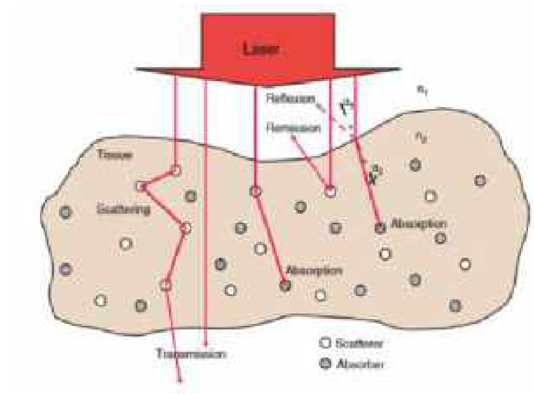
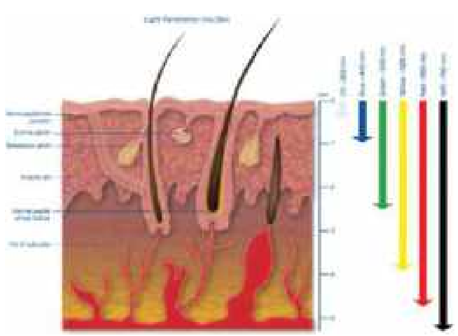
Laser in medicine

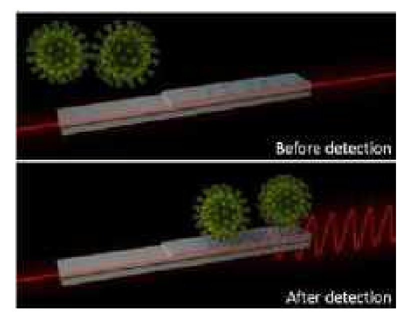


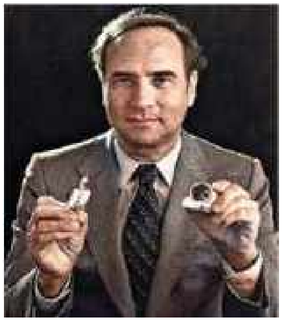
Academic Year: 2023/2024

4th Class - Physics (medical branch)

Lecturer Eman .A. Saied

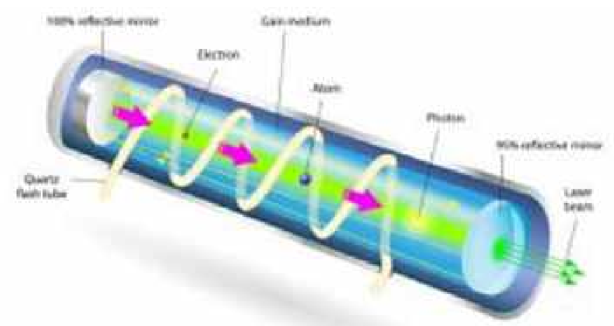


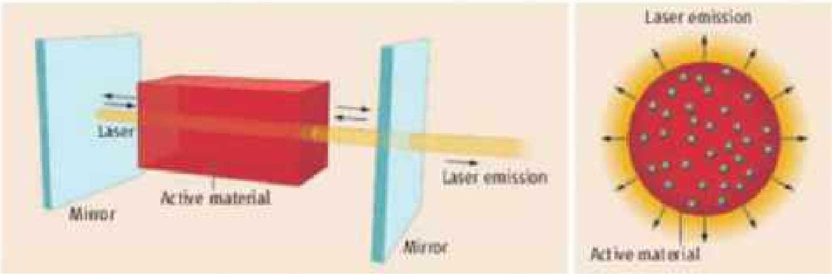


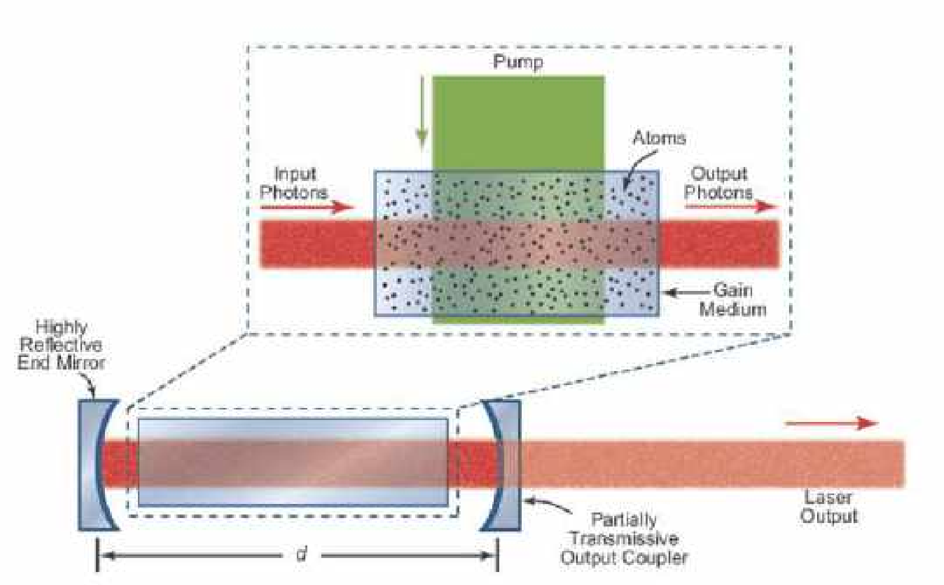


Chapter one

(Introduction to laser principle and theory)







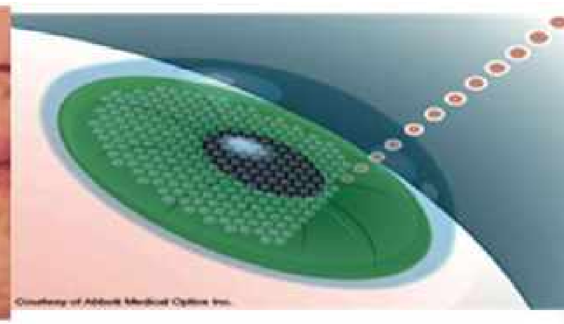
Chapter one

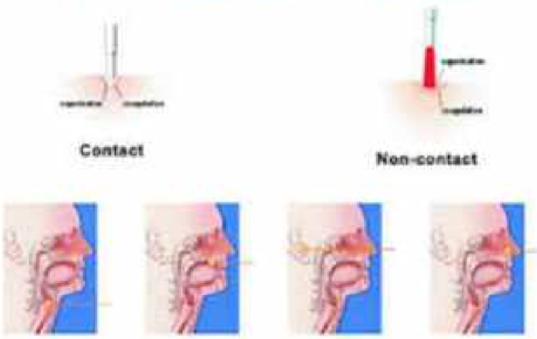
(laser theory, principle)

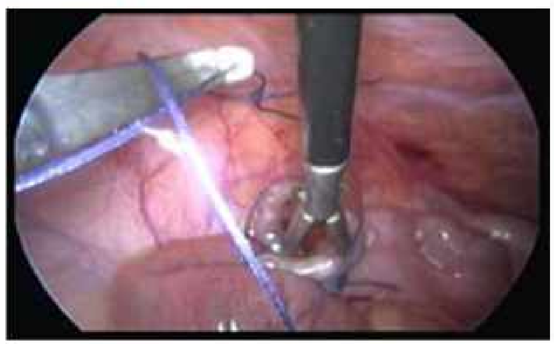
- Why laser
- History of laser
- Absorption , spontaneous and stimulate emission
- laser theory

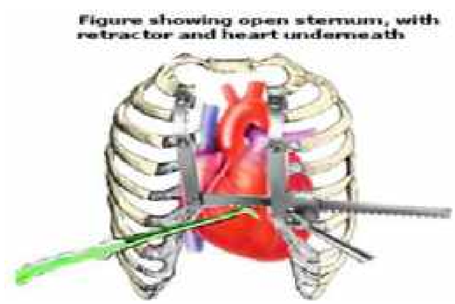
Chapter one :-

Why study laser ?



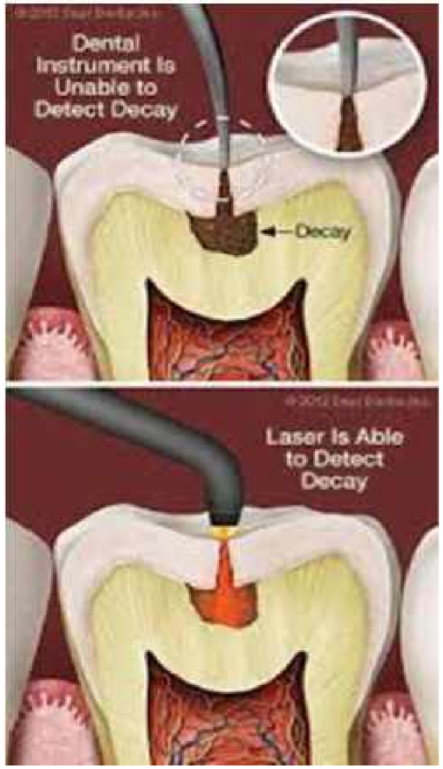




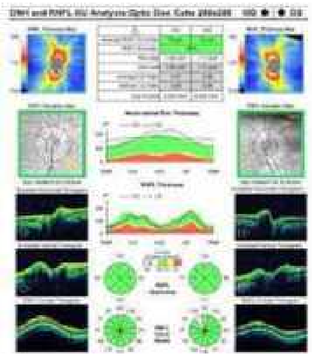


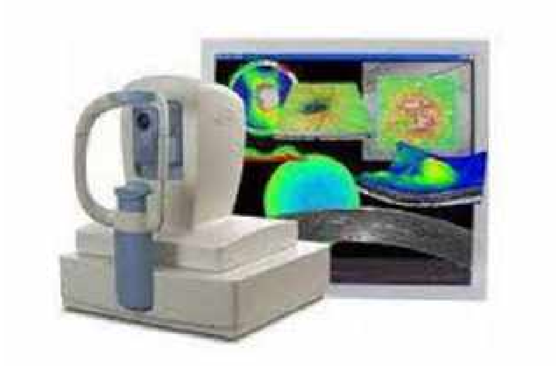
Laser in medicine :- laser in medicine used for

- *Lasers are widely used as tools in imaging and diagnosis: for example, in early detection of cancer and other diseases in patients. Nowadays, laser-based systems are beginning to replace X-rays as laser imaging poses less risk for the patient and has proven to be more accurate in other hand used in dental .*
- .

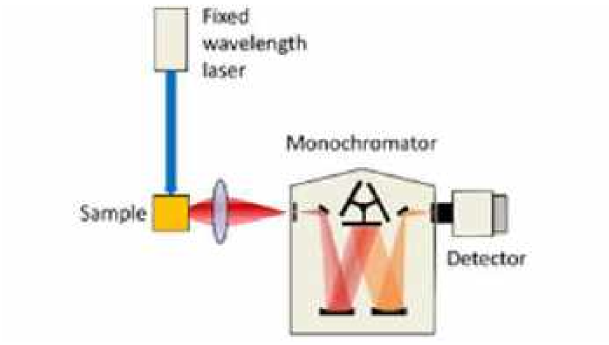


- ***Optical Coherence Tomography (OCT)*** *which uses low-coherence interferometry is already applied in ophthalmology in order to get three-dimensional high-resolution images of the tissues. This enables the ophthalmologist to diagnose retinal diseases or glaucomas. Other diagnostic applications of lasers include*



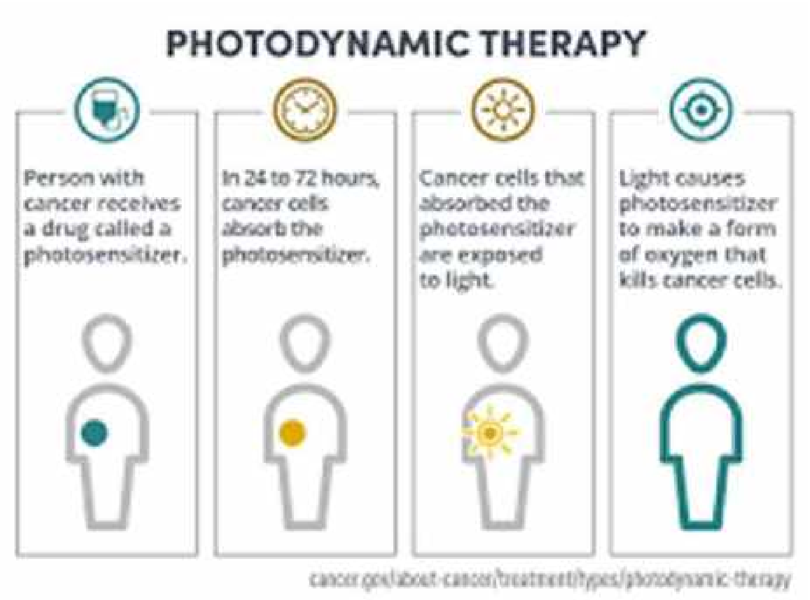


Laser-induced fluorescence (LIF) spectroscopy and imaging or Laser Doppler velocimetry (*LDV) which is a non-invasive method that enables the monitoring of microvascular blood flow.*



- *Treatments :- for example laser treatment for acne.*

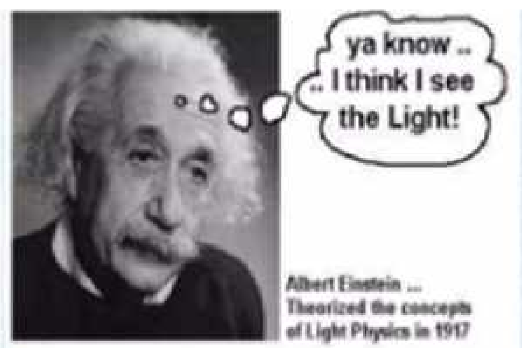
- *Therapies :- such as laser photodynamic therapy*



Introduction to laser Physics

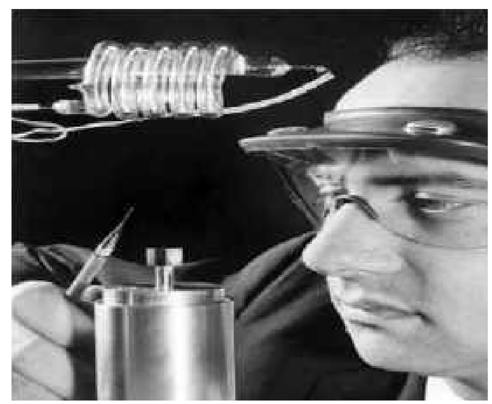
1.1 History of laser

- *1917: On the Quantum theory of radiation – Einstein's paper.*
- *1954: MASER by Townes et al.*
- *Townes (1964) and Schawlow (1981) conceive basic ideas for a laser.*

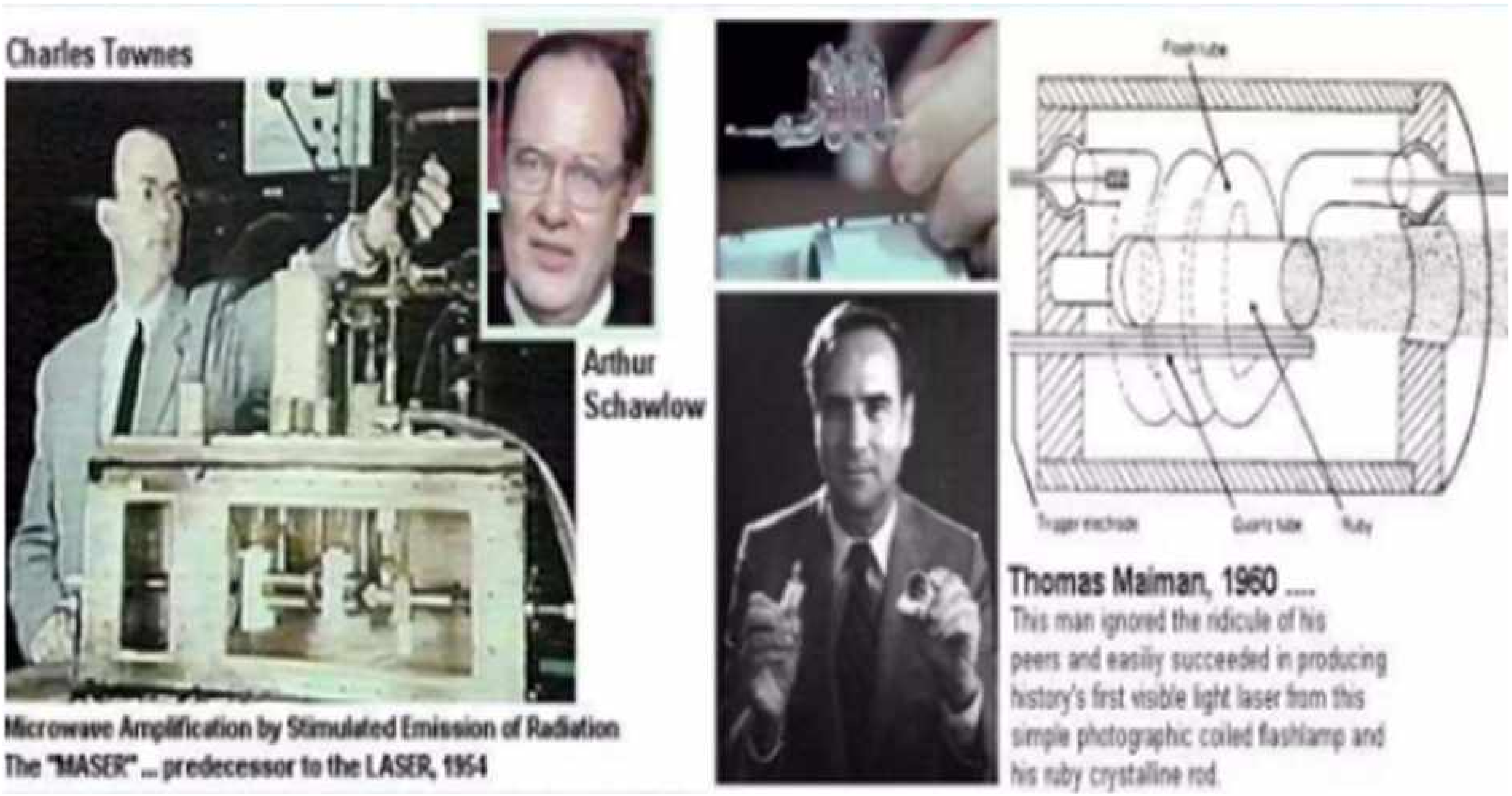


1.1History of laser:-

- In *1960* Maiman build the first operational laser device. It was a ruby laser In 1984 he awarded with the Nobel prize.



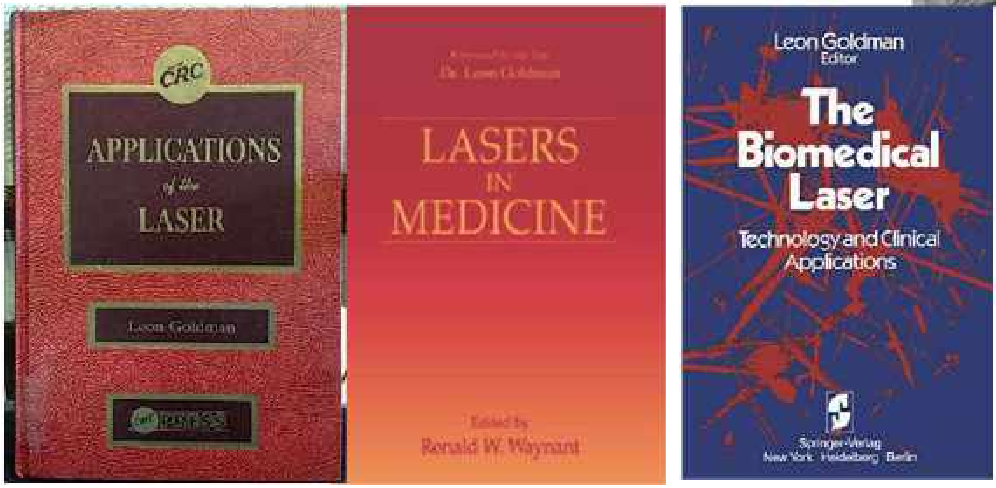
pioneers


Charles Townes
Arthur Schawlow
Microwave Amplification by Stimulated Emission of Radiation
The "MASER" ... predecessor to the LASER, 1954
Thomas Maiman, 1960 ....
This man ignored the ridicule of his peers and easiliy succeeded in producing history's first visible light laser from this simple photographic coiled flashlamp and his ruby crystaline rod.

pioneers

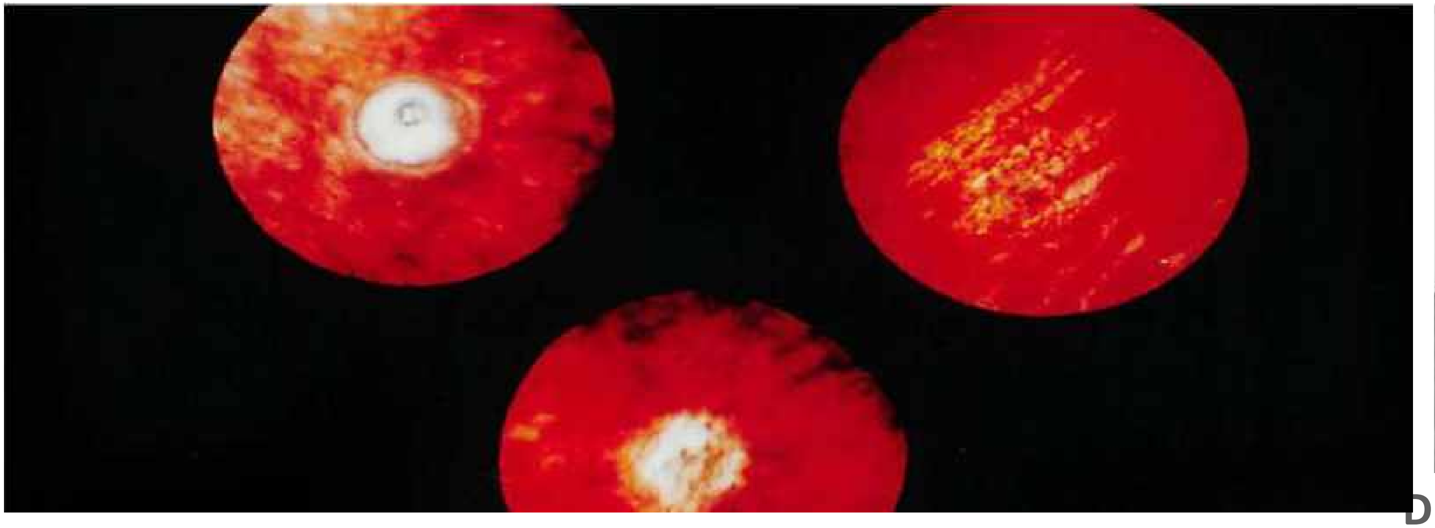
- **Dr. Leon Goldman,** a dermatologist and surgeon who pioneered laser medicine and was the founding president of the American Society of Laser Medicine.
- In 1960, only a year after lasers were invented, he began his research at the University of Cincinnati and later established a laser technology laboratory at the school's Medical Center.

Leon Goldman MD, 1905 - 1997



pioneers

On November 22, 1961, while working alongside ***Dr. Charles Koester,*** *a representative of American Optical Co., which had supplied the laser, Campbell utilized the device to treat a patient's retinal tumor. The tumor, an angioma, was destroyed with a single pulse that lasted about one thousandth of a second. Besides being incredibly fast, the laser was far more comfortable for the patient than the 1,000-watt xenon arc lamps that were being used in similar operations.*



Dr. Charles J. Campbell

HISTORY OF LASER

- **1917** — **Albert Einstein**: On the Quantum Mechanics of Radiation

- **1953** — **Jon Von Neuman**: Described first concept of semiconductor Laser

- **1958** — **Schawlow and Townes**: Invention of MASER

- **1960** — **Maiman**: Built the first working laser

- **1960** — **Ali Javan & William Bennet**: Invented first gas laser

- **1963** — **Chandra Kumar N. Patel**: Developed the carbon dioxide laser

- **1963-64** — **Goldman**: Introduced laser into medical field

- **1977** — **Gordon Gould**: Patent of applications for spectrometry, interferometry, radar, and nuclear fusion.

- **2003** — **Dr. Arvind Patel**: Fiber Laser Machine for Industrial Cuttng

The energy put into the laser can be in any form such as:

- *electromagnetic radiation, electrical energy, chemical energy, etc. Energy is always emitted from the laser as electromagnetic radiation (which includes light beams).*
- *From this light output, the laser got part of its name: LASER = Light Amplification by Stimulated Emission of Radiation.*

The terms used in this definition will be explained later in this course.

- *We will try to obtain a qualitative picture of the quantum nature of the laser, based on some basic principles which came from the advanced mathematical tools.*

laser definition :-

A laser is a device which is built on the principles of quantum mechanics to create a beam of light where all of the photons are in a coherent state — usually with the same frequency and phase.

(Most light sources emit incoherent light, where the phase varies randomly.) Among the other effects, this means that the light from a laser is often tightly focused and does not diverge much, resulting in the traditional laser beam.

Laser is one of the most recent treatment modalities available to physiotherapists.

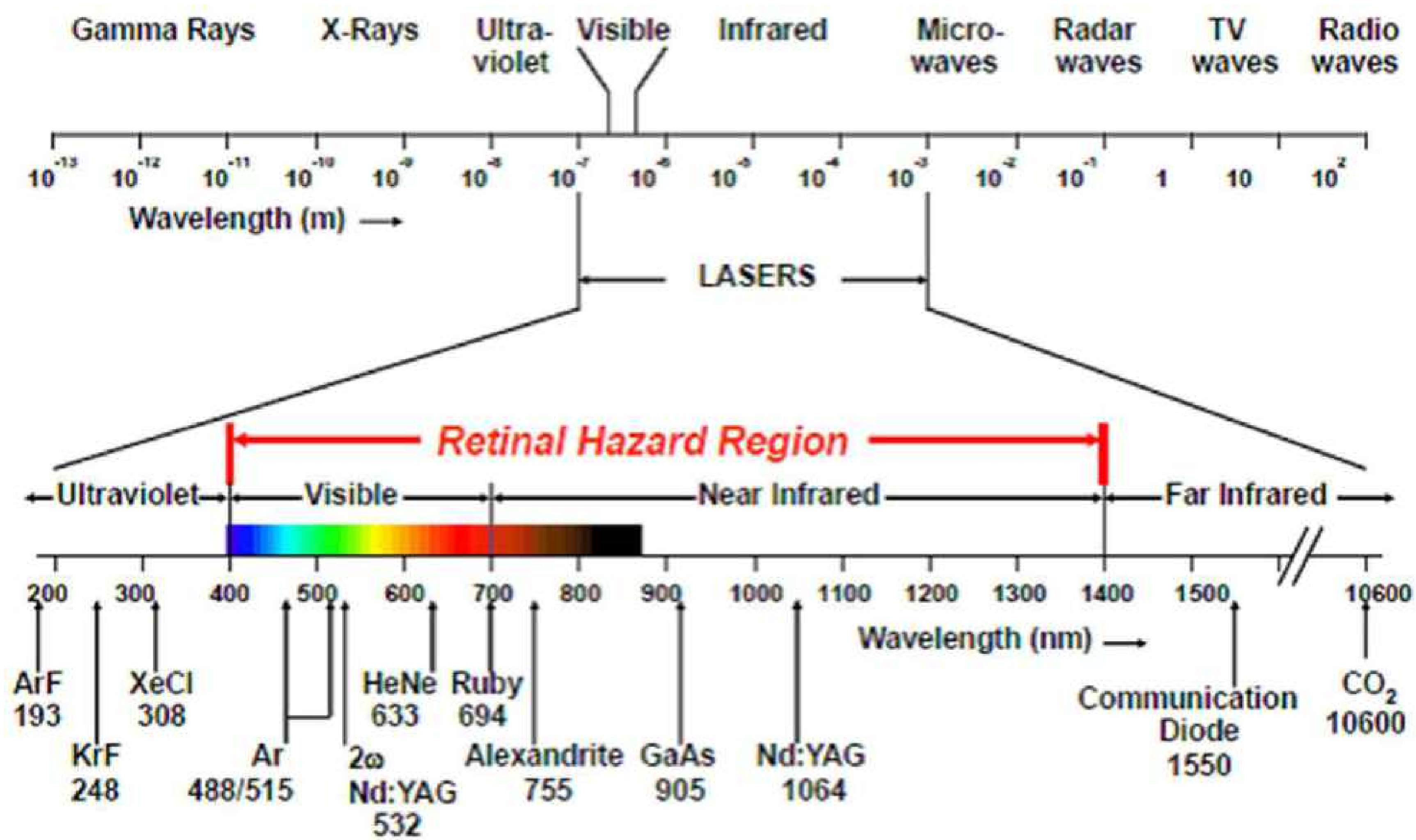
Definition

It is a special form of electromagnetic energy. It has a specific wave length and therefore a specific energy.

The word LASER is an acronym for:

- L ——» Light,
- A ——» Amplification, by
- S ——» Stimulated,
- E ——» Emissions, of
- R ——» Radiation.

It refers to the production of a beam of radiation which differs from ordinary light.


Gamma Rays
X-Rays
Ultra-violet
Visible
Infrared
Micro-waves
Radar waves
TV waves
Radio waves
Wavelength (m)
LASERS
Retinal Hazard Region
Ultraviolet
Visible
Near Infrared
Far Infrared
Wavelength (nm)
ArF 193
KrF 248
XeCl 308
Ar 488/515
2ω Nd:YAG 532
HeNe 633
Ruby 694
Alexandrite 755
GaAs 905
Nd:YAG 1064
Communication Diode 1550
CO2 10600

1.2 Absorption of electromagnetic Radiation

We saw that the process of **photon absorption** by the atom is a process of raising the atom (electron) from a lower energy level into a higher energy level (excited state), by an amount of energy which is equivalent to the energy of the absorbed photon.

Our discussion involved a **microscopic system** in which one photon interacts with one atom. In a **macrosc-opic system**, when electromagnetic radiation passes through matter, part of it is transmitted, and part is absorbed by the atoms.

The **intensity (I)** of the transmitted radiation through a thickness (x) of homogeneous material, is described by the experimental equation of exponential absorption (**Lambert Law**):

$$I=I_0\exp(-\alpha x)$$

I_0 = Intensity of incoming radiation.

α = Absorption coefficient of the material.

The thicker the material (bigger x), the lower the transmitted beam.

The **transmission (T)** of this material is described by the relation between the transmitted intensity (I) to the incident intensity (I_0):

$$T=I/I_0$$

From the last two equations we get the Transmission:

$$T = \exp(-\alpha x)$$

the units of the absorption coefficient (α) are: [cm^{-1}]

Every material is transparent differently to different wavelengths, so **the absorption coefficient (α) is a function of the wavelength:** $\alpha(\lambda)$.

This fact is very important (as we shall see) to understand the interaction of electromagnetic radiation with matter, in the variety of applications of the laser

Results from the exponential absorption law:

- *For every material,* ***absorption depends on the width of the material****. The thicker the material, less radiation will be transmitted through.*
- *For a certain width (x) of the material, absorption depends only on the* ***absorption coefficient (α), which is characteristic of each material****.*

Decay Rate

Energy loss by an excited atom can be performed in two basic ways:

*•**Non-radiative decay** - by transferring the energy to mechanical vibrations of neighboring atoms. The rate for this type of decay is γ_{nr}. The macroscopic effect of these vibrations is what we call heat (or rise in temperature).*

*•**Radiative decay** - by spontaneous emission at a rate γ_{rad}.*

*The **total decay rate** of a certain level is the sum of the decay rates of the two processes:*

$$\gamma = \gamma_{nr} + \gamma_{rad}$$

Orders of magnitude for decay lifetime for atoms:

***Non radiative decay**: picoseconds - microseconds (10^{-12} - 10^{-6} [sec]) - **very fast**.*

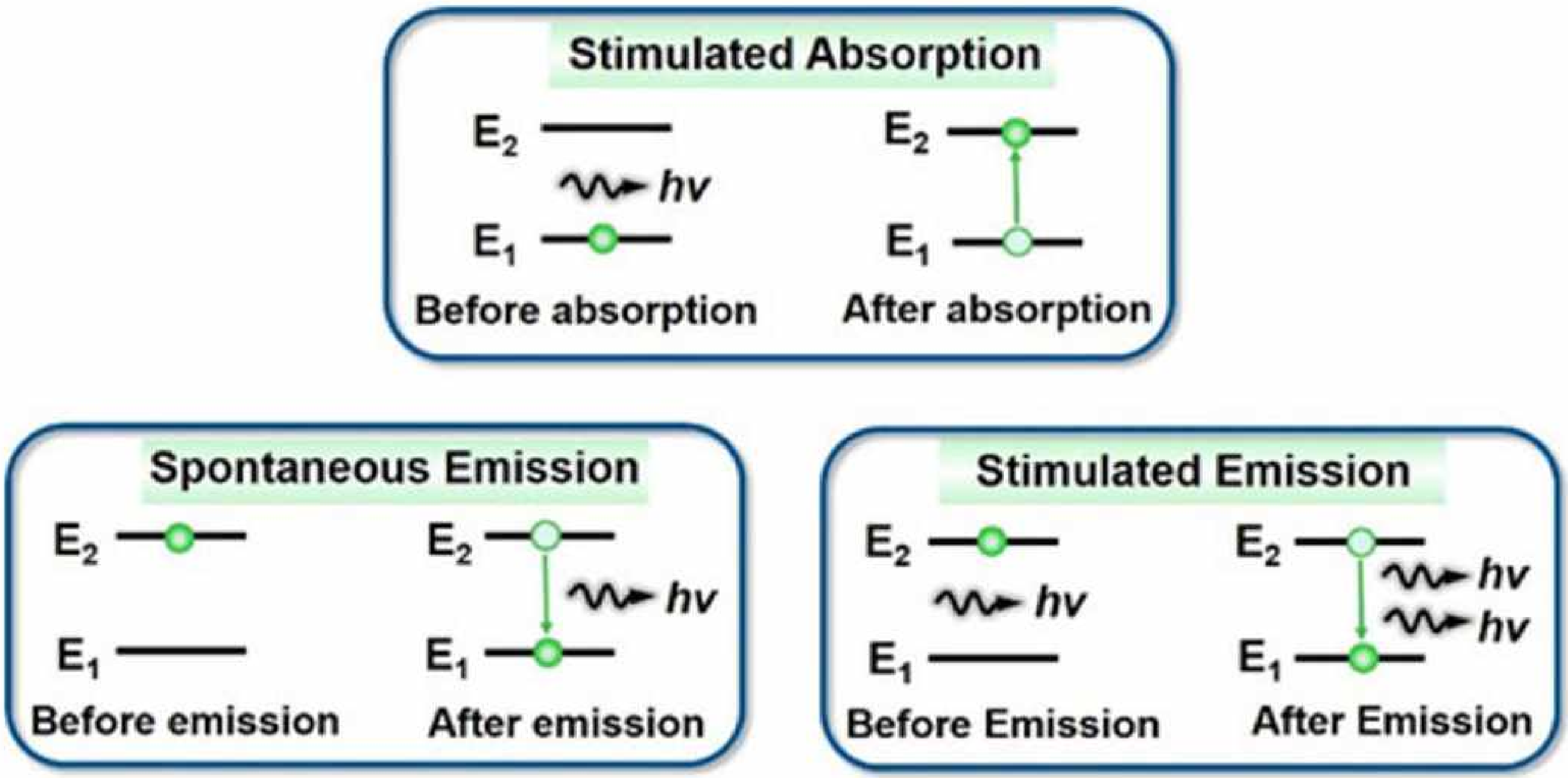
***Radiative decay:** microseconds - milliseconds (10^{-6} - 10^{-3} [sec])*

The three different mechanisms are shown below :

1. Absorption*: An atom in a lower level absorbs a photon of frequency hv and moves to an upper level.*

2. ***Spontaneous emission:*** *An atom in an upper level can decay spontaneously to the lower level and emit a photon of frequency hv if the transition between E2 and E1 is radiative. This photon has a random direction and phase.*

3. ***Stimulated emission:*** *An incident photon causes an upper level atom to decay, emitting a "stimulated" photon whose properties are identical to those of the incident photon. The term "stimulated" underlines the fact that this kind of radiation only occurs if an incident photon is present. The amplification arises due to the similarities between the incident and emitted photons.*


Stimulated Absorption
E2
hv
E1
Before absorption
E2
E1
After absorption
Spontaneous Emission
E2
E1
Before emission
E2
hv
E1
After emission
Stimulated Emission
E2
hv
E1
Before Emission
E2
hv
hv
E1
After Emission

1.4 Boltzmann distribution of atom .

the atoms distribution in different energy levels with different numbers, relating to the original No. of atoms and Absolute temperature of media suppose in any state of energy (E) the number of unchanged atoms are N then the decreases in their number is proportional to the energy differential in that state and the No. of a atoms in that state as

$$-dN \propto NdE \Rightarrow dN = -cNdE$$

$$\frac{dN}{N} = -cdE$$

$$\int_{N}^{No} \frac{dN}{N} = -\int_{0}^{E} cdE$$

$$or \quad \frac{N}{N_0} = e^{-cE}$$

Analysis show that this constant is 1/KT where K is Boltzmann constant ,T is the absolute temp.

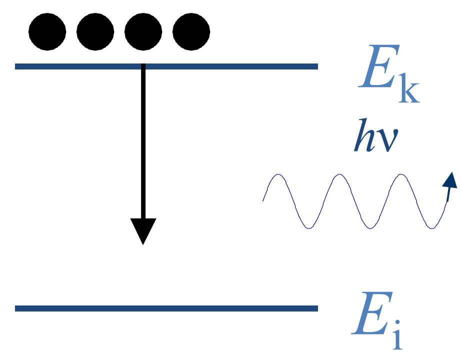
$$\therefore N = N_0 e^{\frac{-E}{KT}}$$

(***Boltzmann distribution***)

For the case of only two energy levels E1 and E2 having two population density N1 and N2 then eq(1) could be written as:-

$$\therefore N_1 = N_0 e^{\frac{-E_1}{KT}}$$

$$\therefore N_2 = N_0 e^{\frac{-E2}{KT}}$$



N1 > N2

By division the above equation

$$\therefore \frac{N_1}{N_2} = e^{\frac{-E2-E1}{KT}}$$

The last two equ. Shows that at room temperature , No. of atoms in the lower level is much more than that of higher level , so for a system of many energy states :E1,E2,….ect. Having population densities N1.N2,…ect. The plot of this is shown in the following graph:-

Practically even for very small energy difference between states 1 and 2 and for very high temperature N2 can not be equal to N1 This is called Natural or Boltzmann distribution of atomic population :

A system with a population inversion is not in thermal equilibrium; populations of energy levels are <u>*not*</u> governed by the Boltzmann distribution

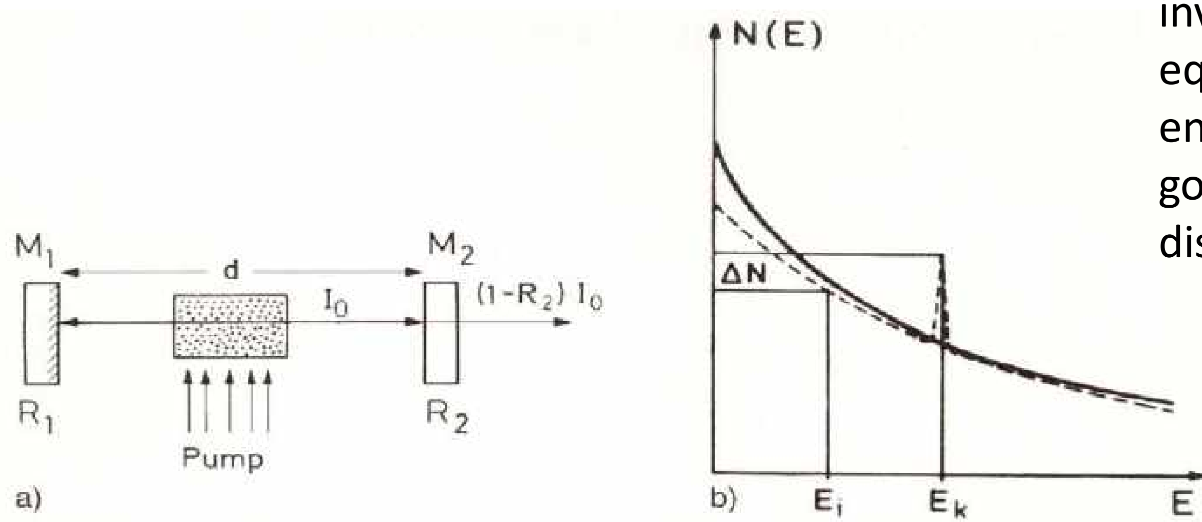
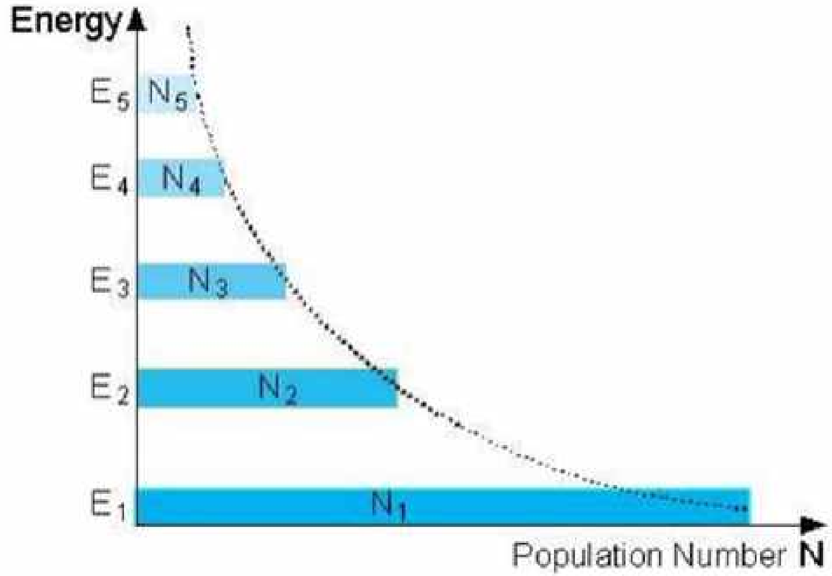


Fig. 5.1. (a) Schematic setup of a laser and (b) population inversion (*dashed curve*), compared with a Boltzmann distribution at thermal equilibrium (*solid curve*)

The Figure below shows the population of each energy level at thermal equilibrium.

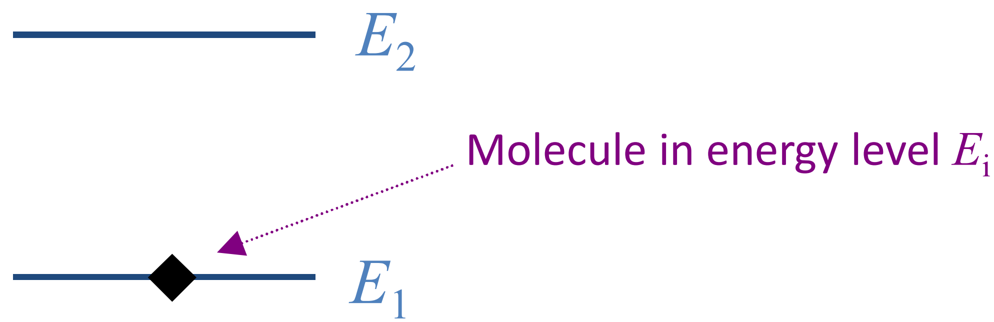


Population Numbers at "Normal Population"

1.5 Population inversion

Absorption and Emission of radiation

Consider an atom or molecule with two energy levels, E_1 and E_2

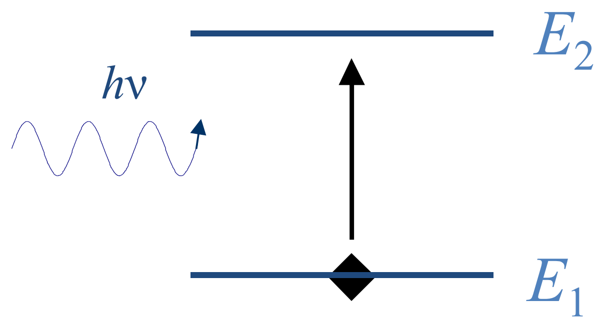


A direct, radiative transition between these states would be associated with a photon of frequency ν: $h\nu = \Delta E = E_2 - E_1$

Three possible transitions:

(a) "Induced absorption":

Molecule in E_1 absorbs a photon and is excited to E_2



One *less* photon of energy $h\nu$

Probability of transition is: $\mathrm{d}N_{12}/\mathrm{d}t = \mathrm{N}_{12} B_{12}\, \rho(\nu)$

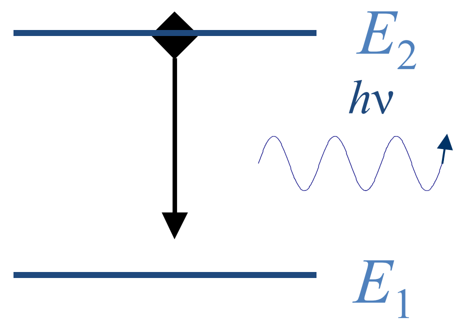
$\mathrm{d}N_{12}/\mathrm{d}t$ is the probability per second of a molecule absorbing a photon

B_{12} is the *Einstein coefficient of induced absorption*

$\rho(\nu)$ is the *spectral energy density* (the number of photons of frequency ν per unit volume)

(b) "Spontaneous emission":

Molecule in E_2 decays spontaneously to E_1 by emitting a photon in an arbitrary direction



One *more* photon of energy $h\nu$ (arbitrary phase & direction)

Probability of transition is $\mathrm{d}N_{21}/\mathrm{d}t = N_{21}A_{21}$

$\mathrm{d}N_{21}/\mathrm{d}t$ is the probability per second of the excited molecule emitting a photon

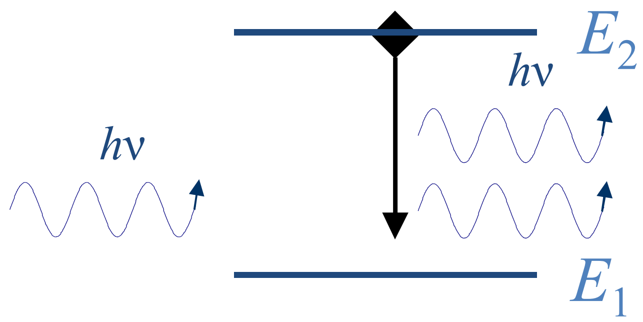
A_{21} is the *Einstein coefficient of spontaneous emission* (or the *spontaneous transition probability*)

Spontaneous emission is *not* influenced by the presence of other photons in the medium

Absorption and Emission of radiation

(c) "Induced emission" (or "stimulated emission"):

A photon of appropriate frequency induces the transition from E_2 to E_1



One *more* photon of energy $h\nu$. The new photon has the same *frequency*, *phase*, and *direction* at the original photon

Probability of transition is $\mathrm{d}N_{21}/\mathrm{dt} = \mathrm{N}_{21} B_{21}\,\rho(\nu)$

- $\mathrm{d}N_{21}/\mathrm{d}t$ is the probability per second of the excited molecule emitting a photon
- B_{21} is the *Einstein coefficient of induced emission*

Absorption = spontaneous emission + stimulate emission

$$N_{12} B_{12} \rho(v) = N_{21} A_{21} + N_{21} B_{21} \rho(v)$$

Or

$$N_{1} B_{12} \rho(v) = N_{2} A_{21} + B_{21} \rho(v)$$

$$\rho = \frac{A_{21} / B_{21}}{\frac{N_1}{N_2} - 1}$$

But at steady state
B12=B21

Now No. of Spo. Emission /No. of Stu. Emission=

$$\frac{N_2 A_{12}}{\rho B_{21}} = \frac{A_{12}}{B_{21}} \frac{1}{\rho}$$

But

$$\rho = \frac{A_{21} / B_{21}}{\frac{N_1}{N_2} - 1}$$

$$\therefore \frac{N_1}{N_2} = e^{\frac{h\upsilon}{KT}} = \frac{n_{spo.}}{n_{stu}}$$

Relation between B_{12} and B_{21}:

The Einstein coefficients of induced absorption and emission are directly related through the degeneracy, g_x, of each level x:

$$B_{12} = (g_2/g_1)\, B_{21}$$

In the case where each level has the same degeneracy ($g_1 = g_2$), the Einstein coefficients of induced absorption and emission are identical
– in other words, the probability of induced emission is ***the same*** as that of induced absorption

How can we make practical use of induced emission?

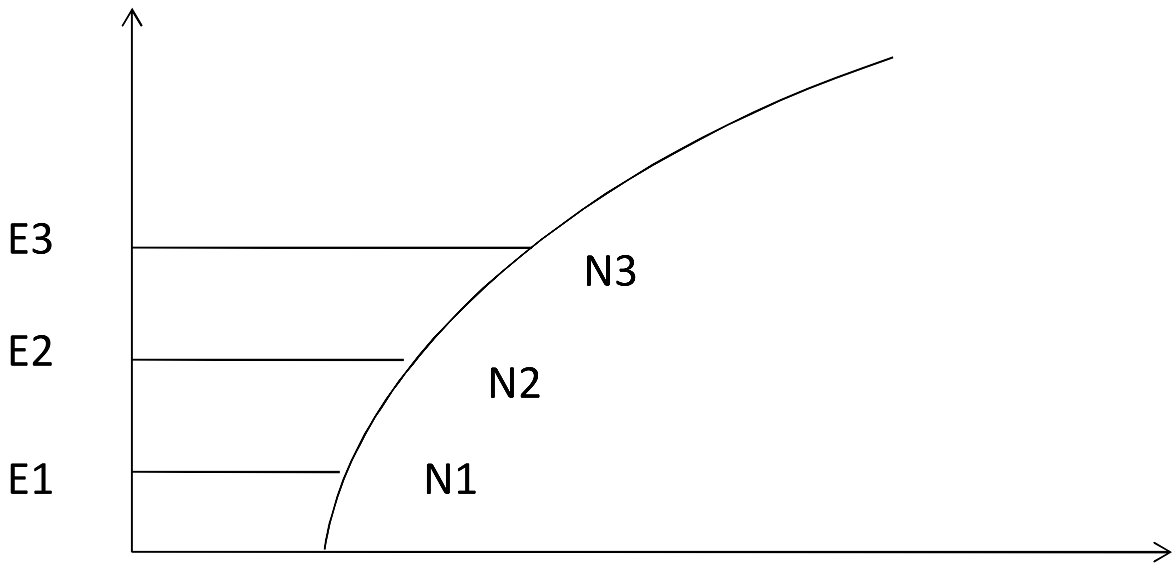
$B21 = B12 = 1 \qquad E2 - E1 = h\upsilon$

$$\rho(r) = \frac{A21}{B21}\left[\frac{1}{e^{\left(\frac{h\upsilon}{KT}\right)} - 1}\right]$$

$$\rho(r) = \frac{8\pi h\upsilon^3\mu^3}{c^3}\left[\frac{1}{e^{\left(\frac{h\upsilon}{KT}\right)} - 1}\right]$$

$$\frac{A21}{B21} = \frac{8\pi h\upsilon^3\mu^3}{c^3}$$

In pop. Inversion case having more electron in high energy level at which fluorescent emission starts than , in lower energy level at which the emission terminates.



1.6 Absorption or Amplification:

From the equation of rate of loss of energy from the incoming signal, we see that **the sign of the difference in the population number ($\Delta N = N_1(t)-N_2(t)$)** determines if the energy density of the incoming signal will increase or decrease as a function of time.

Consider **two possible situations:**

1.When a collection of atoms is in a **normal population (Thermal equilibrium**), The population number of the lower energy level **(E_1)** is higher than the population number of the higher energy level **(E_2):** $N_1(t) > N_2(t)$.
In this situation **only absorption is possible**, and as a result the atoms will receive energy from the incoming signal which will decrease in magnitude.

2.When a collection of atoms is in a **population inversion,** The sign in front of the parenthesis is minus, and the signal will increase - **Amplification !**
Energy from the system of atoms will be transferred to the incoming signal, and amplify it at a rate which is proportional to the difference in population numbers and to the intensity of the incoming signal.

Conclusion:

If a material is in a thermal equilibrium, only absorption can occur, and no amplification.

To produce **amplification**, the material must be in a **population inversion** in which more atoms are pumped to an excited state as compared to a lower state.

After understanding the amplification process at the **microscopic level** of atoms, we shall connect this process to the **macroscopic system**, as we did in the process of absorption of electromagnetic radiation.

In the process of **absorption** in the laser medium, the **absorption coefficient (α)** depends on the material, and on the difference in population numbers **($\Delta N = N_1(t)-N_2(t)$)** between the energy levels E_1 and E_2, as:

$$\alpha = K(N_1 - N_2)$$

The **proportionality constant (K)** depends on the material and the wavelength of the laser radiation.

As long as $N_1(t)>N_2(t)$, α is positive, and the process is **absorption**.

In the "**population inversion**" situation, $N_1(t)-N_2(t) < 0$, so that $N_2(t)>N_1(t)$, than **α is negative**.

According to Lambert law: $I = I_0 e^{-\alpha x}$, **the factor ($-\alpha x$)** is positive, which means that **the intensity at the output (I) is bigger than the intensity at the input (I_0)**, thus **amplification (gain of energy)**.

In case of **amplification**, α is called **Gain Coefficient**.

Attention

The **probability of the stimulated transition** by the incoming radiation is identical for the two processes (absorption and stimulated emission). The direction in which more processes will occur depends on the population of the energy levels at that moment.

Example Dependence of amplification on the length of the laser `A laser is 15 [cm] long. For a certain wavelength, the amplification of the laser is 1.5.
Calculate the amplification of this laser if the length of the active medium is 30 [cm].

Solution to Example
using the definition of amplification:

$$\text{Amplification} = \frac{I}{I_0} = e^{-\alpha \cdot x}$$

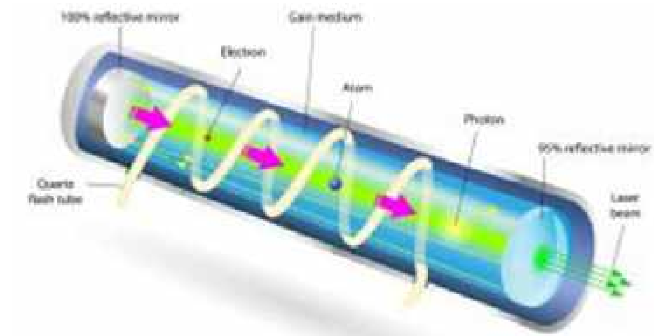
substitute the known parameters:

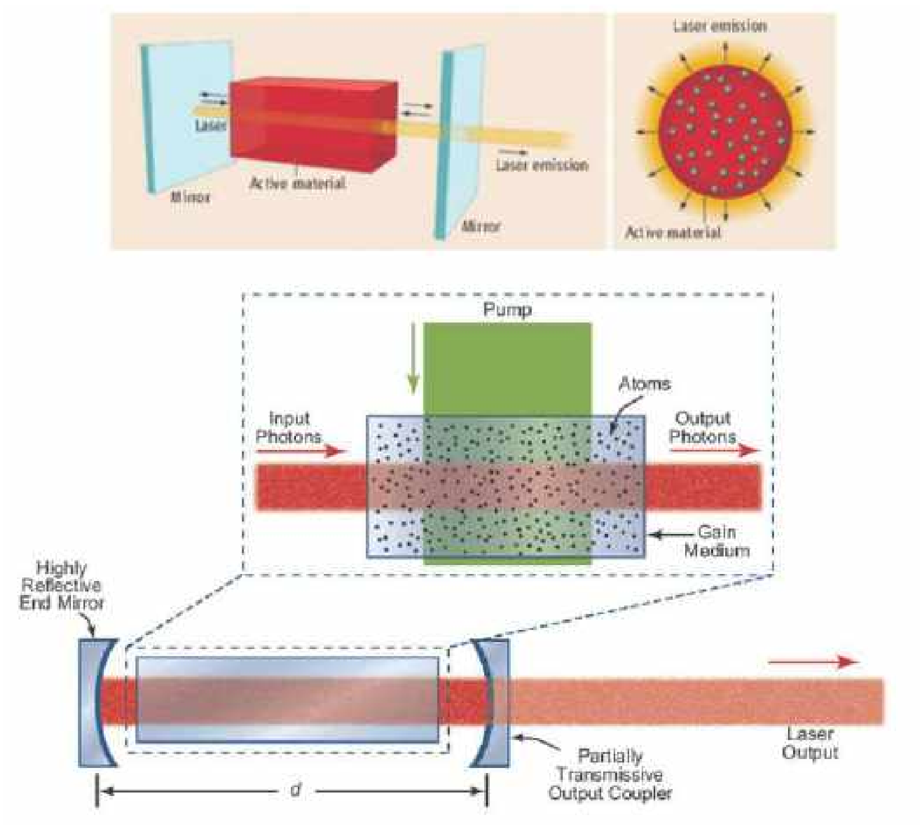
$$1.5 = e^{-\alpha \cdot 15}$$

we get:
α = -0.027 [cm^{-1}]
using the new length in the amplification definition:

$$\text{Amplification} = \frac{I}{I_0} = e^{-\alpha \cdot x} = e^{-\left(-0.027 \cdot cm^{-1} \cdot 30 \cdot cm\right)} = 2.25$$

1.8 Laser theory





laser theory :-

1.8.1 Active medium

Three level system.

1Four level system.

1.8.2 pumping source, types of pumping source.

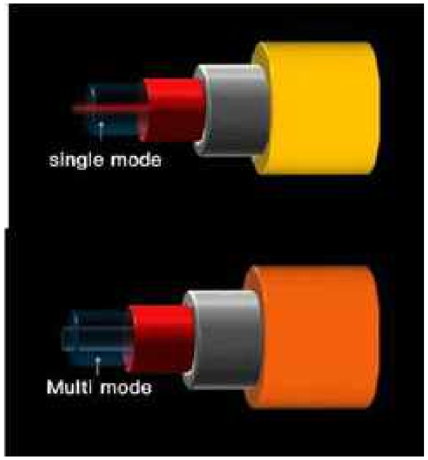
1.8 .3 Resonators.

plane parallel (fabry-perrot)resonators.

Stable resonator.

Unstable resonator.

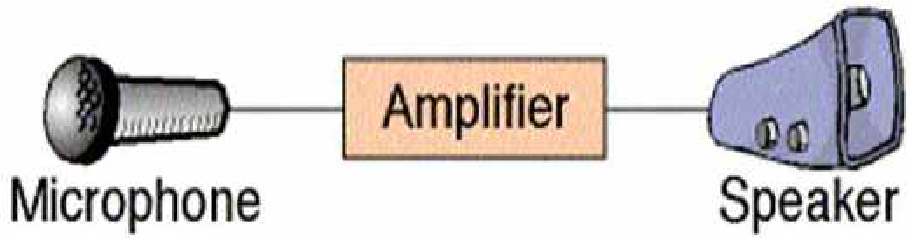
Resonator modes



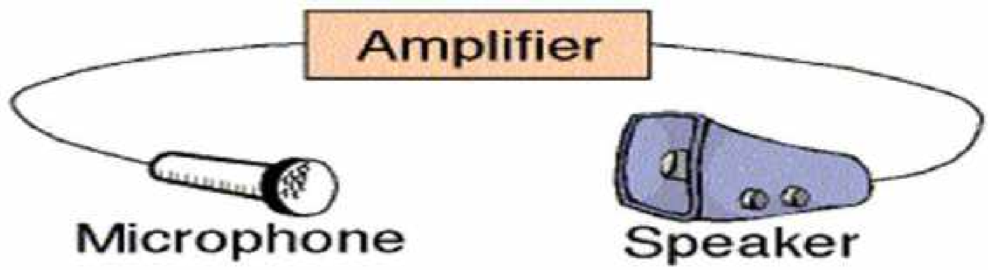
The Laser System

The laser is a system that is similar to an **electronic oscillator**.
An **Oscillator** is a system that produces oscillations without an external driving mechanism.
To demonstrate an oscillator, we can use the familiar acoustic analog:

A sound amplification system has a **microphone, amplifier** and **speaker**.



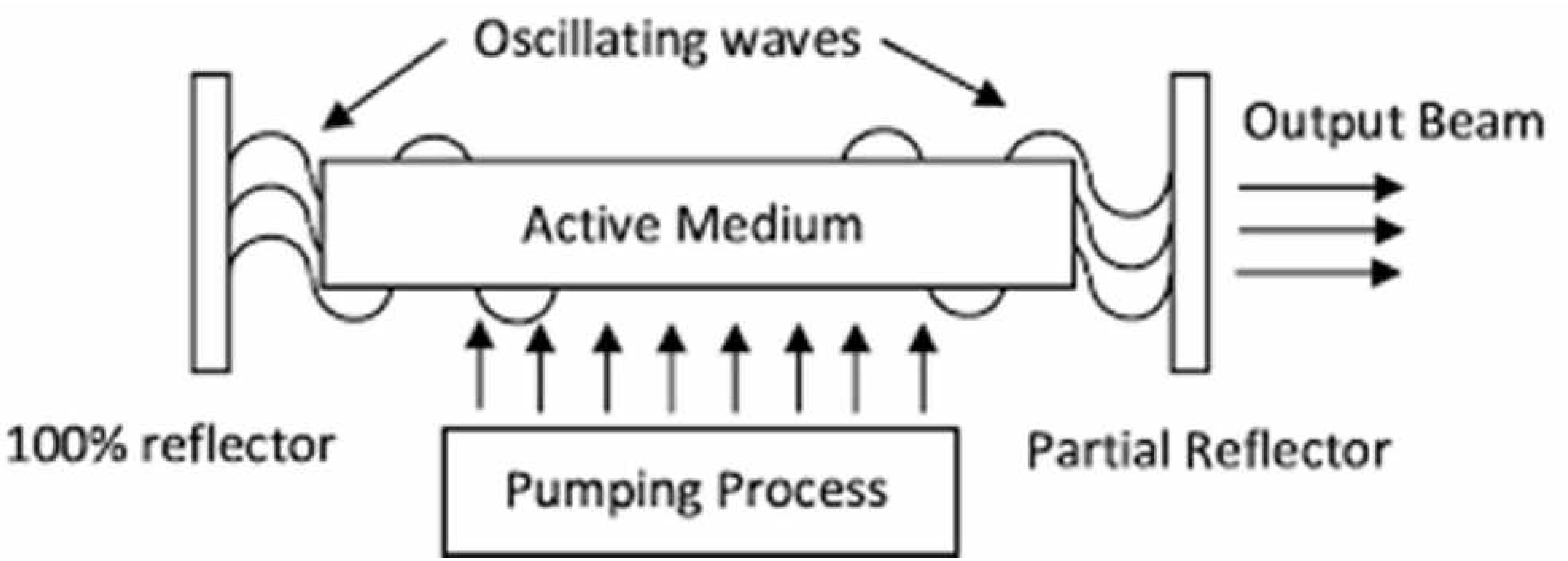
When the microphone is placed in front of the speaker, a **closed circuit** is formed, and a whistle is heard out of the speaker.

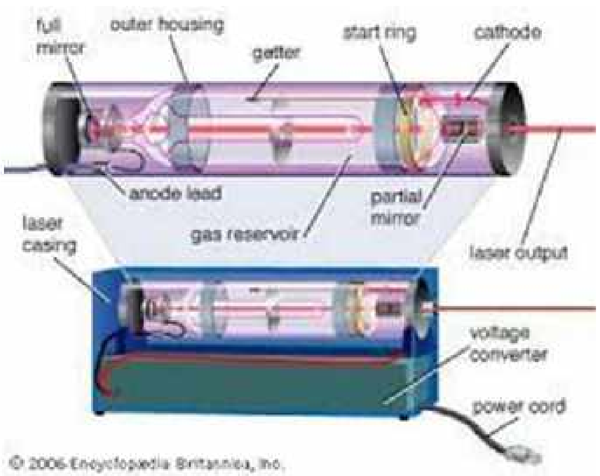


The whistle is created spontaneously, without any external source.

Explanation: The speaker's internal noise is detected by the microphone, amplified and the amplified signal is again collected by the microphone. This **positive feedback** continues until a loud whistle is heard.

Laser main parts

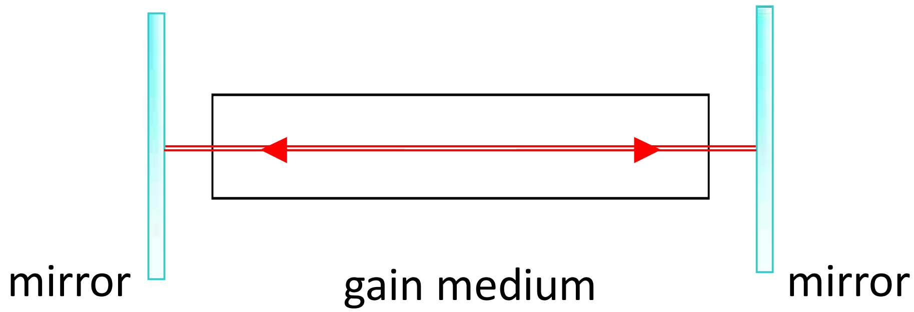




The amount of amplification of the incident beam in a single pass is small, a fraction of a percent/centimetre of travel.

To increase the path length through the sample could use either:

- A very long laser/gain medium.
- Mirrors to reflect the beam back into the sample.



- The gain medium is the substance which can support the population inversion, can be solid, liquid or gas.
- The combination of the gain medium and the mirrors is called the laser cavity or the optical resonator.

laser active medium:

•The **active medium** is a collection of atoms or molecules, which can be excited into a **population inversion** situation, and can have electromagnetic radiation extracted out of it by stimulated emission.

•**The active medium determines the possible wavelengths that can be emitted from the laser**. These wavelengths are determined by the specific transitions between the laser energy levels in this material.

The list of materials that laser under certain laboratory conditions include hundreds of substances, and the number increases with time. **The basic physics of the laser is similar for all types of lasers**, and we will use the term "**Active Medium**" and assume that it is composed of "**atoms**". In reality, the active medium can be atoms, molecules, ions, or semiconductors, according to the laser type.

Why do we not have 2-level lasers?

First condition for laser action

If $N_1 > N_2$

- ***If most molecules in state 1, then incoming radiation is mainly absorbed.***
- ***Incident radiation is <u>attenuated</u> (reduced).***

If $N_2 > N_1$

- ***If most molecules are in state 2, absorption of***
- ***incoming radiation is hindered.***
- ***The result is stimulated emission.***
- ***Incident radiation is <u>amplified</u>.***

Thus for laser action require a <u>population inversion</u>, $N_2 > N_1$

How to obtain a population inversion

Consider the Boltzman equation.

$$\frac{N_2}{N_1} = \exp\left(\frac{-\Delta E}{kT}\right)$$

When kT is large, the ratio of $N_2/N_1 \approx 1$, equal numbers of molecules in state 1 and state 2.

When kT is small the ratio of $N_2/N_1 \approx 0$ and all molecules are in state 1.

Cannot obtain a population inversion using thermal methods in a 2 level system.

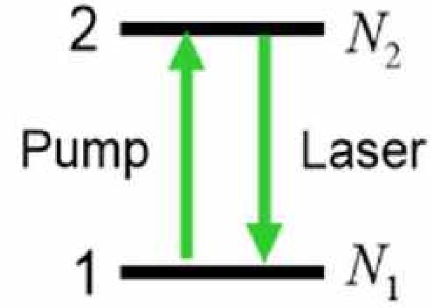
- Multi-level systems must be employed.
- Molecules need to be pumped into a higher energy state.

Various methods : electrical discharge, flashlamp excitation.

- Continuous pumping gives a Continuous Wave (CW) Laser.
- Pulsed pumping gives a Pulsed Laser (PL) output.

Rate equations for a two-level system

Rate equations for the population densities of the two states:



Absorption, Stimulated emission, Spontaneous emission

$$\frac{dN_2}{dt} = BI(N_1 - N_2) - AN_2$$

Pump intensity (I)

$$\frac{dN_1}{dt} = BI(N_2 - N_1) + AN_2$$

If the total number of molecules is N:

$$N \equiv N_1 + N_2$$

$$\Delta N \equiv N_1 - N_2$$

$$\Rightarrow \quad \frac{d\Delta N}{dt} = -2BI\Delta N + 2AN_2$$

$$2N_2 = (N_1 + N_2) - (N_1 - N_2) = N - \Delta N$$

$$\Rightarrow \quad \frac{d\Delta N}{dt} = -2BI\Delta N + AN - A\Delta N$$

$$\frac{d\Delta N}{dt} = -2BI\Delta N + AN - A\Delta N$$

In steady-state: $0 = -2BI\Delta N + AN - A\Delta N$

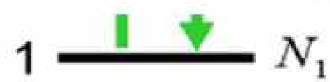
Solve for ΔN: $(A + 2BI)\Delta N = AN$

$$\Rightarrow \quad \Delta N = AN/(A+2BI) = \frac{N}{1+\frac{2B}{A}I}$$

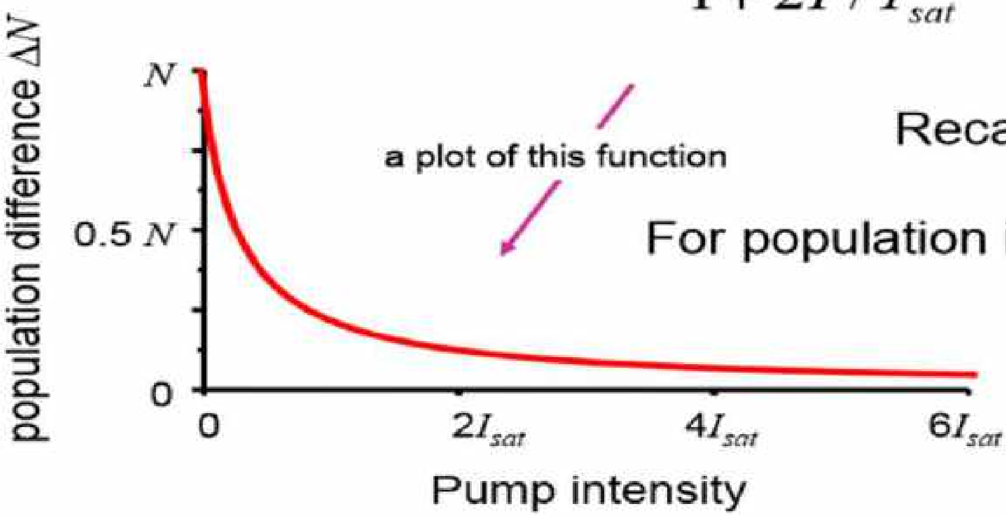
$$\Rightarrow \boxed{\Delta N = \frac{N}{1+2I/I_{sat}}}$$

where: $I_{sat} = A/B$

I_{sat} is called the **saturation intensity**.



Population difference $\Delta N = \dfrac{N}{1+2I/I_{sat}}$



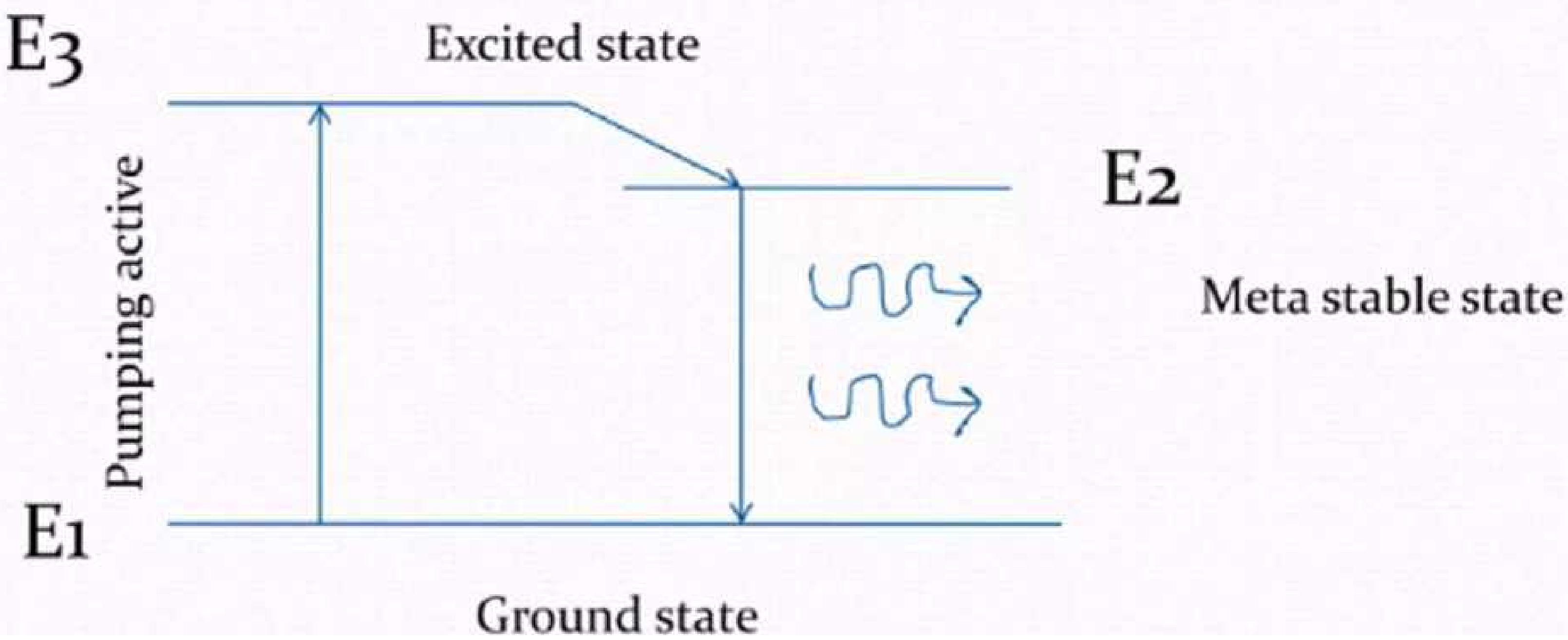
Recall that $\Delta N \equiv N_1 - N_2$

For population inversion, we require $\Delta N < 0$

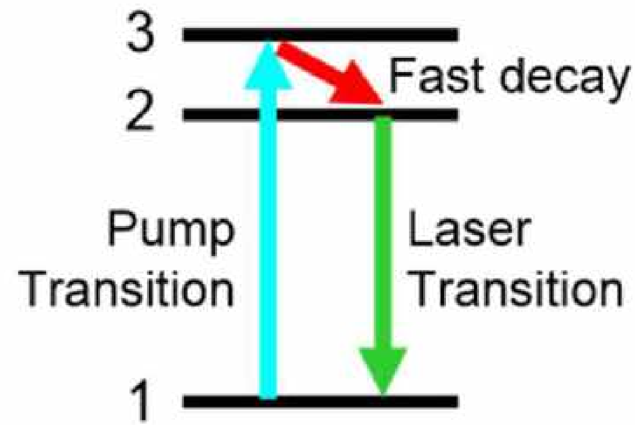
ΔN is always positive, no matter how hard we pump on the system!

Three level laser system

The simplest kind is three level laser which uses and assembly of atom or molecules that have three energy states E1,E2,E3.
Where, E1-> ground state
E2->meta stable state
E3->higher excited state



Rate equations for a three-level system



So, if we can't make a laser using two levels, what if we try it with three?

Assume we pump to a state 3 that rapidly decays to level 2.

$$\frac{dN_2}{dt} = BIN_1 - AN_2$$

$$\frac{dN_1}{dt} = -BIN_1 + AN_2$$

The total number of molecules is N:

$$N \equiv N_1 + N_2$$

$$\Delta N \equiv N_1 - N_2$$

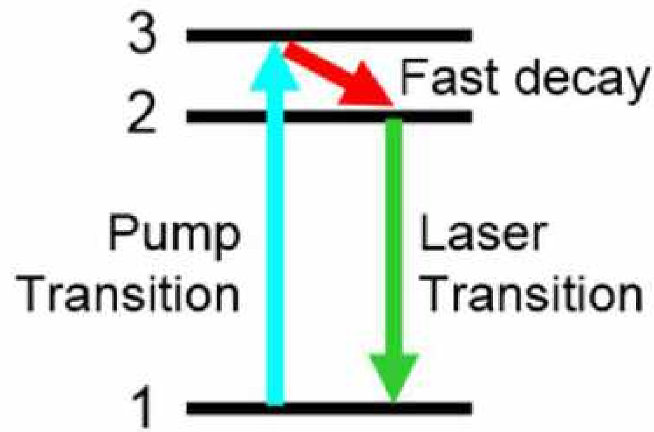
Level 3 decays fast and so $N_3 = 0$.

$$\frac{d\Delta N}{dt} = -2BIN_1 + 2AN_2$$

$$2N_2 = N - \Delta N$$

$$2N_1 = N + \Delta N$$

Why inversion is possible in a three-level system



$$\frac{d\Delta N}{dt} = -BIN - BI\Delta N + AN - A\Delta N$$

In steady-state: $0 = -BIN - BI\Delta N + AN - A\Delta N$

Solve for ΔN: $\Delta N = N\frac{A - BI}{A + BI} = N\frac{1-(B/A)I}{1+(B/A)I}$

$$\Rightarrow \boxed{\Delta N = N\frac{1 - I/I_{sat}}{1 + I/I_{sat}}}$$

where, as before: $I_{sat} = A/B$

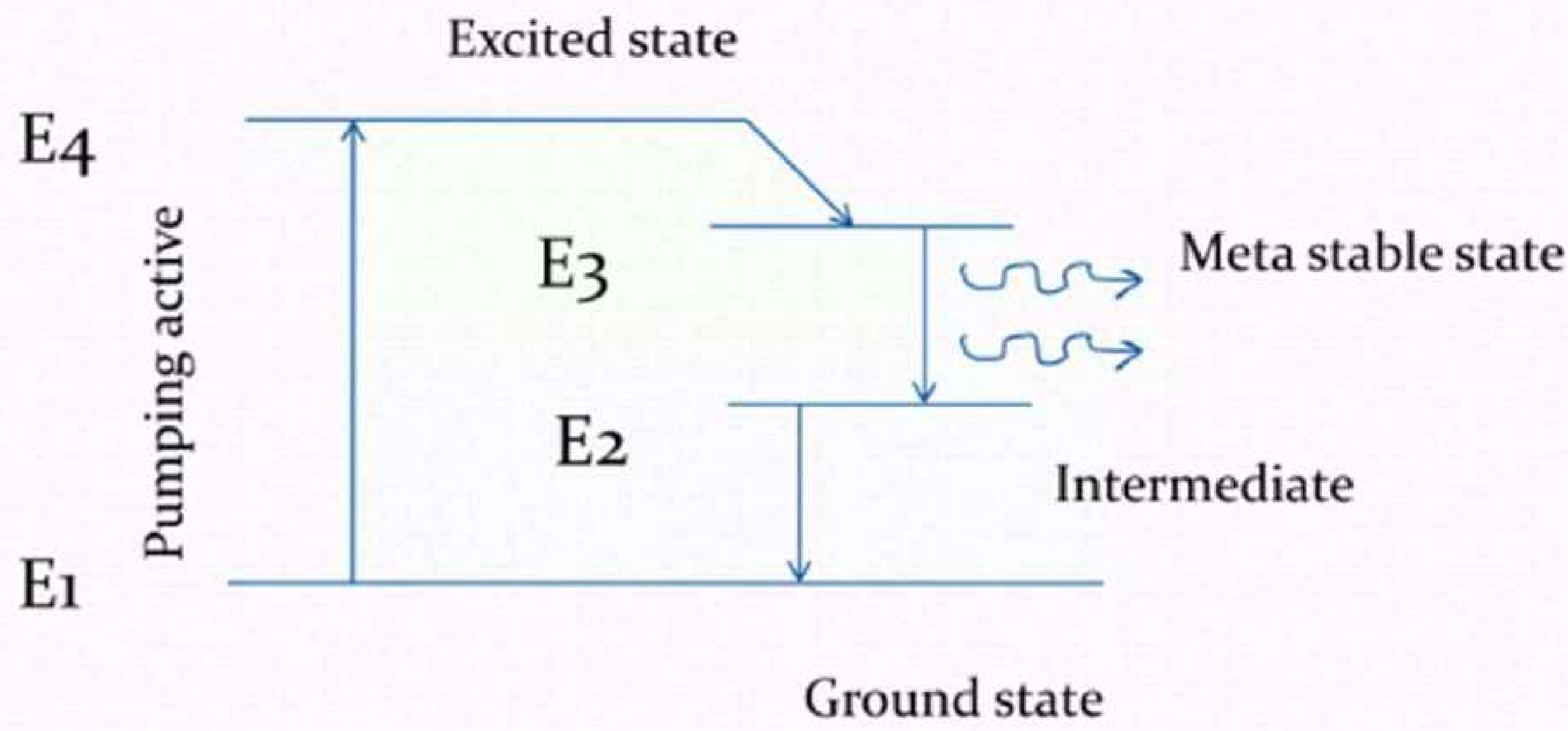
I_{sat} is the **saturation intensity**.

Now if $I > I_{sat}$, ΔN is negative!

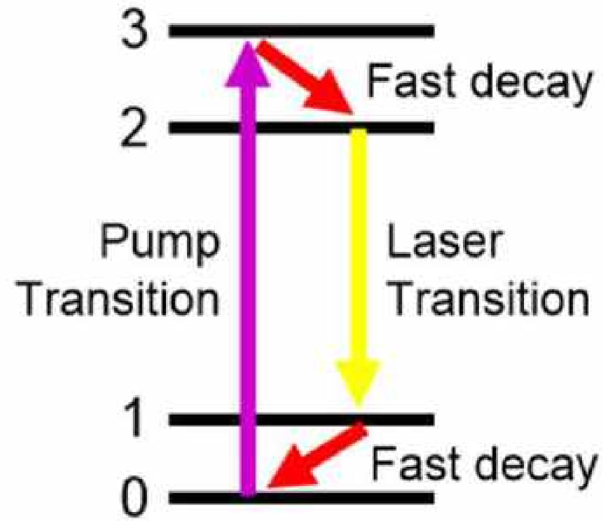
[redacted]

Four level laser system

E1->ground state,E2->intermediate,E3->metastable,E4->excited state



Rate equations for a four-level system



Now assume the lower laser level 1 also rapidly decays to a ground level 0.

As before: $$\frac{dN_2}{dt} = BIN_0 - AN_2$$

The total number of molecules is N:

$$N \equiv N_0 + N_2$$

$$N_0 = N - N_2$$

$$\frac{dN_2}{dt} = BI(N - N_2) - AN_2$$

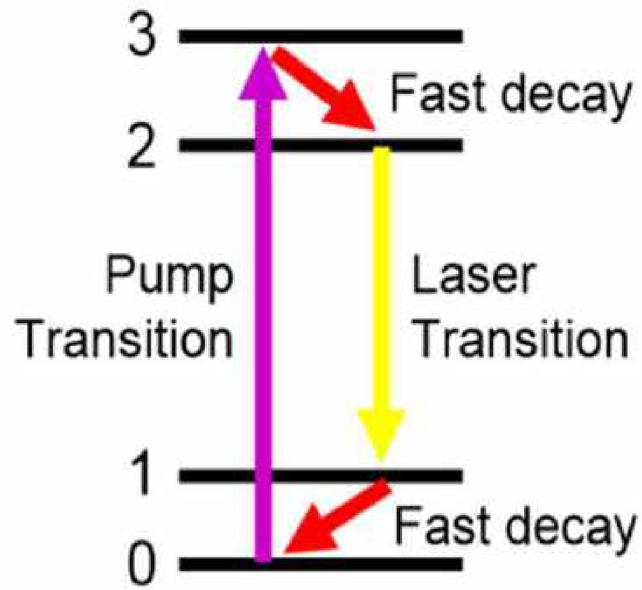
Because $N_1 \approx 0,\quad \Delta N \approx -N_2$

$$-\frac{d\Delta N}{dt} = BIN + BI\Delta N + A\Delta N$$

At steady state: $$0 = BIN + BI\Delta N + A\Delta N$$

[redacted]

Why inversion is easy in a four-level system



$$0 = BIN + BI\Delta N + A\Delta N$$

Solve for ΔN:

$$\Rightarrow \quad \Delta N = -BIN/(A + BI) = -N\frac{(B/A)I}{1+(B/A)I}$$

$$\Rightarrow \quad \boxed{\Delta N = -N\frac{I/I_{sat}}{1+I/I_{sat}}}$$

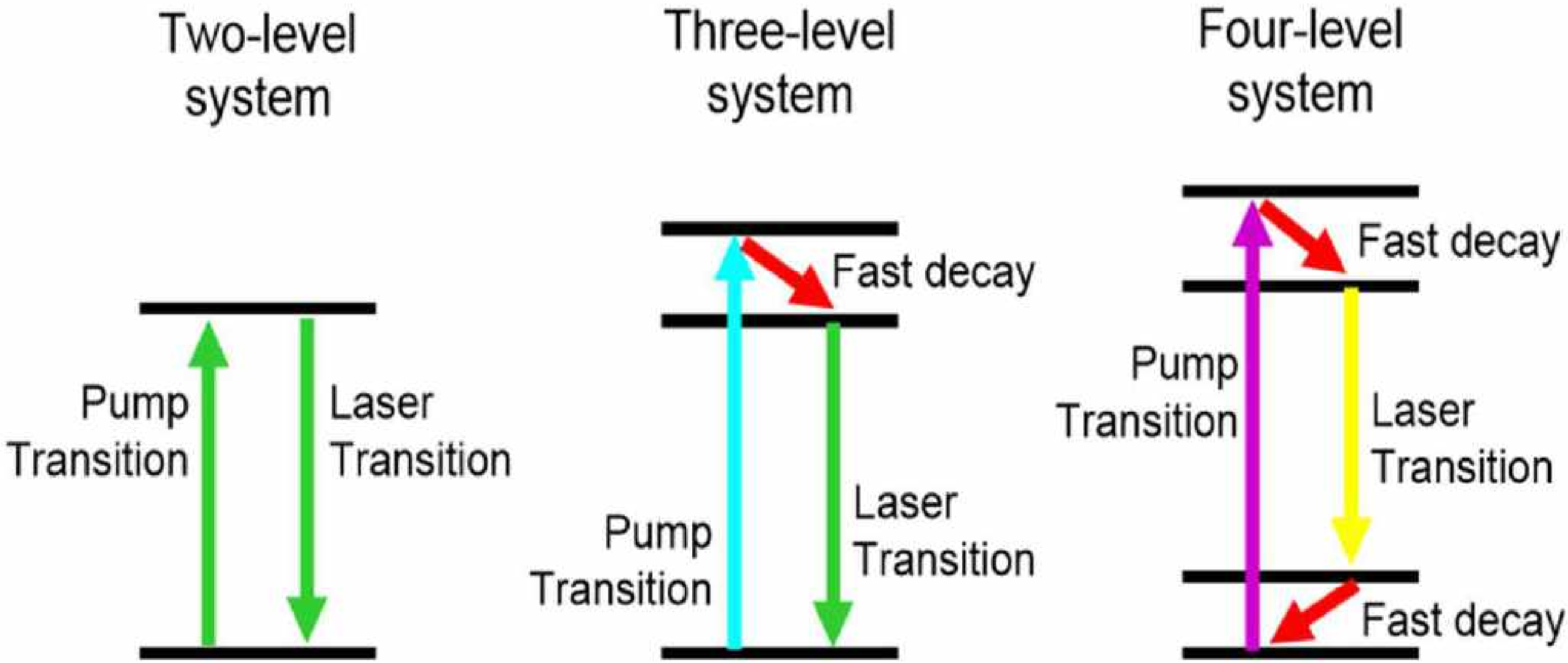
where: $I_{sat} = A/B$

I_{sat} is the **saturation intensity**.

Now, ΔN is negative—for any non-zero value of I!

Two-, three-, and four-level systems

Four-level systems are best.



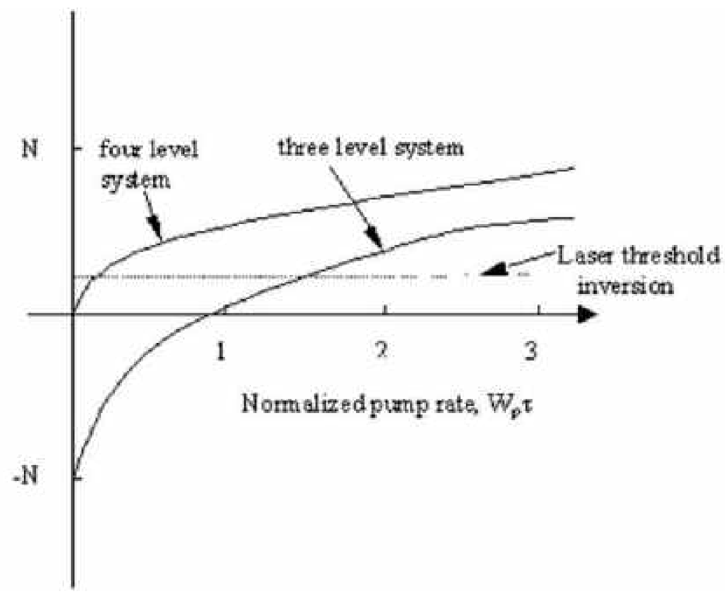
At best, you get equal populations. No lasing

If you hit it hard, you get lasing.

Lasing is easy!

Three energy level Laser	Four energy level laser
Requires three energy level	Requires four energy level
The out put is pulsed	The output is continuous
Lasing occur once	Lasing occur at upper and lower lasing lev
Require higher pumping rate	Require higher pumping rate
Continous operation impossible	Continous operation possible
Ruby laser is common example	He-Ne and Nd:YAG lasers are examples

Table: Comparison of three level laser and four level laser



2.2 pumping source, types of pumping source (active media).

The excitation mechanism or pumping sources:

*The **excitation mechanism** is the source of energy that raises the atoms in the active medium into their excited state, thus creating population inversion.*

In accordance to the law of conservation of energy, the electromagnetic radiation out of the laser is always less than the input energy by the excitation mechanism. There are lasers with efficiency of much less than 1% (!), while others with efficiencies approaching a 100%.

*There are **few types of excitation mechanisms:***

Methods of population Inversion:-

There are many methods for gating a population inversion these methods depended on many factors for example type and state of active media and the type of laser power and wave length .

The main classic types are :-

1- Electrical pumping.

-Direct electron excitation.

-collision of the second type.

2- optical pumping.

3- chemical pumping.

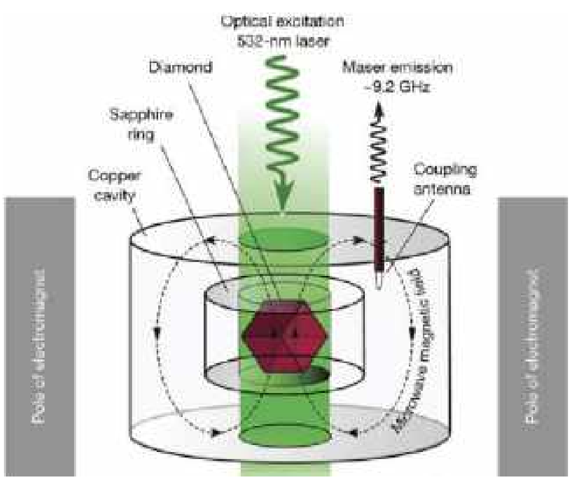
PUMPING MECHANISMS

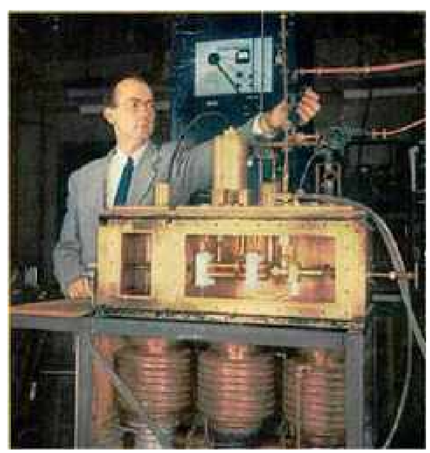
How can the energy be input to a collection of atoms or molecules to create a population inversion?

You know the energy cannot be put in thermally; that would just heat the collection, not create a population inversion.

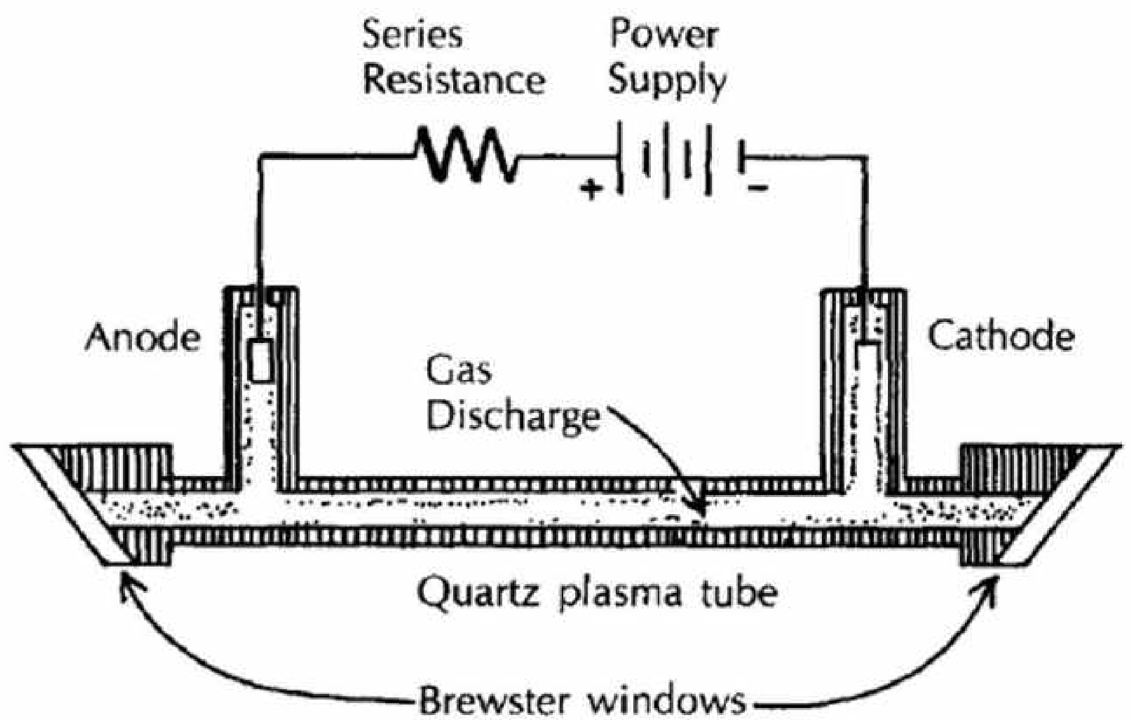
The very first laser-like device ever built, the ammonia maser (microwave amplification by stimulated emission of radiation) created a population inversion that way. Ammonia molecules were forced through a filter that selectively blocked molecules in the lower of two energy levels so that the molecules that emerged exhibited a population inversion.

That technique has not proven successful with modern lasers.





Electrical pumping

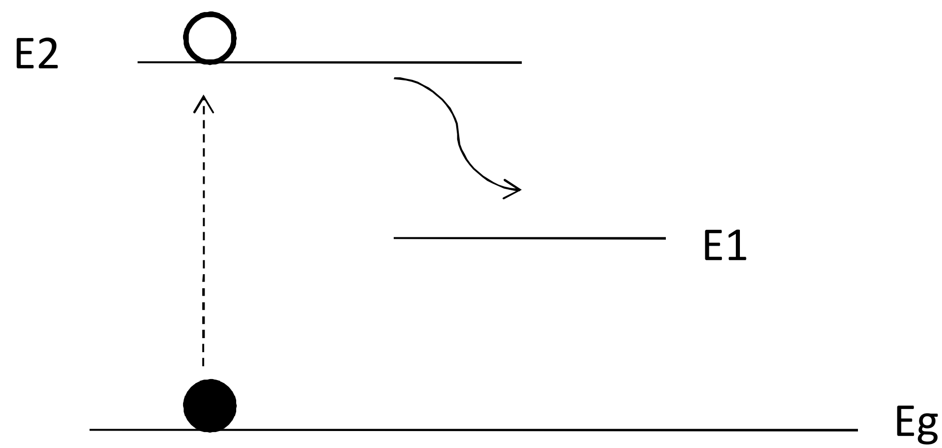


Electrical discharge pumping can create a population inversion.

A- Direct electron excitation

This could be done through a gaseous discharge and it is used to produced the desired inversion , this method use is used in some of the gaseous ion laser , in this method a beam of High –energies electrons in directed through a collection of atom at least-state of energy then the electron , will loose their extra energy and transferring the atoms to the exited state As shown:-

$$e^{*} + A \longrightarrow e + A^{*}$$

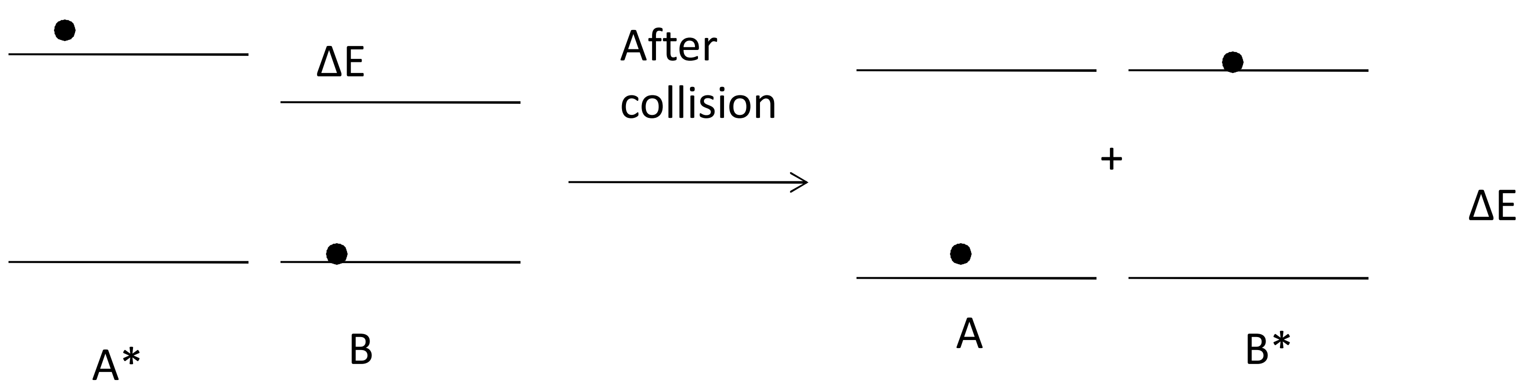


B- collision of the second Kind :-

In this method two kinds of atoms precipitate one of them is originality in an exited state (possibility meta- stable – stable state) and the other in other in ground state ,after the collision the first kind decay to the ground state resulting excitation of the second kind

He- Ne laser for example

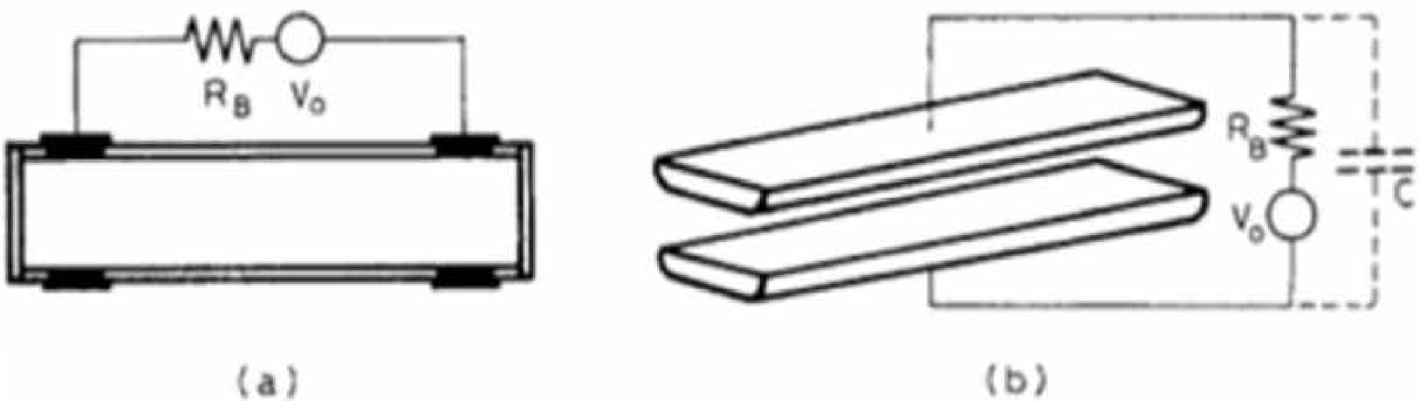
$$A^* + B \longrightarrow A + B^* + \Delta E$$



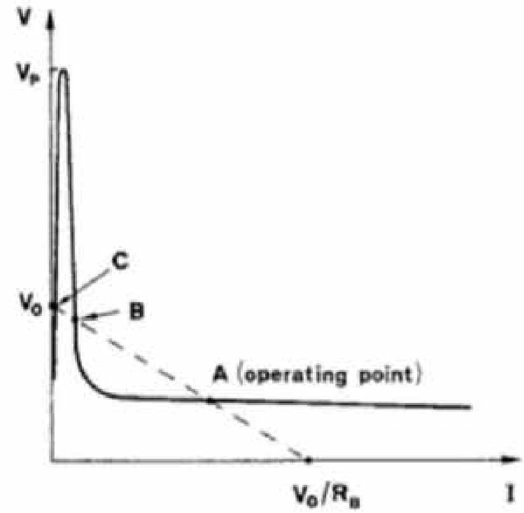
Electrical pumping :-

1- longitudinal pumping

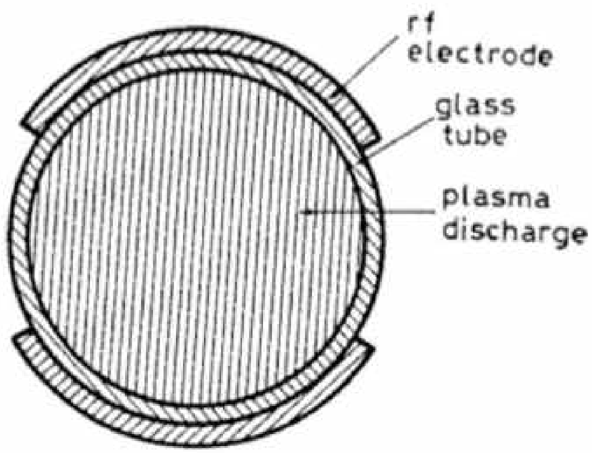
2- transverse pumping



Most frequently used pumping configurations for gas-discharge lasers: (a) Longitudinal discharge. (b) Transverse discharge.



. Voltage, V, vs current, I, characteristic of a gas discharge (solid line) and of a power supply with a series resistance (dashed line).

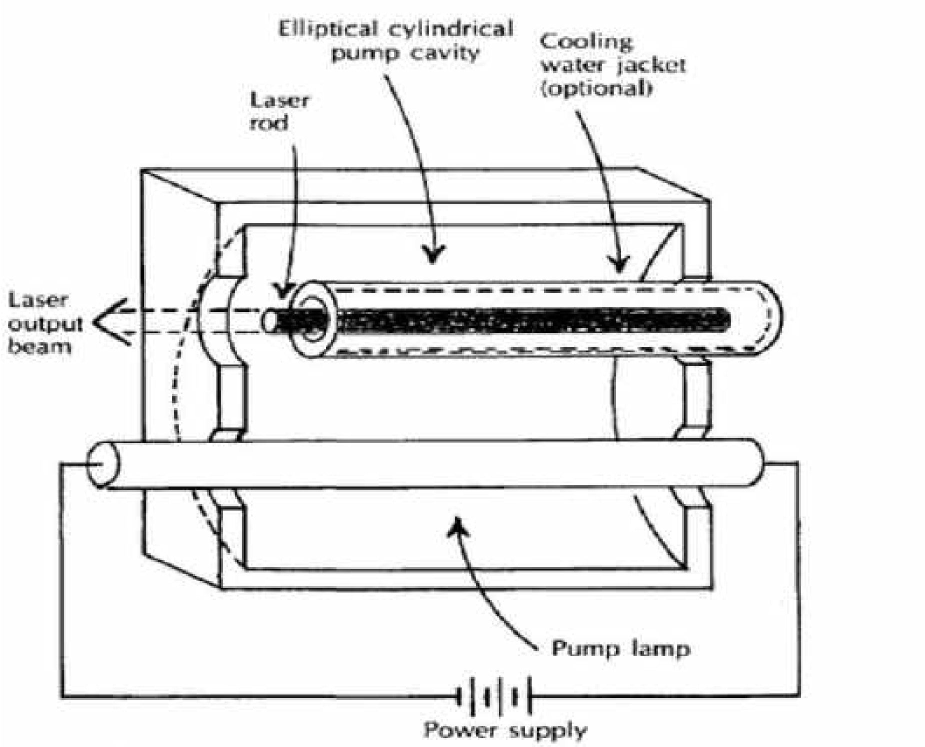


Radio-frequency transverse excitation of a gas in a quartz tube.

2- Optical pumping

In this method a beam of light with a proper wave-length and intensity is employed by directing it through the material in question through which the atom will be exited to the higher state the degree of the population inversion depended upon the time- rate of the pumping

$$A + h\nu \longrightarrow A^*$$

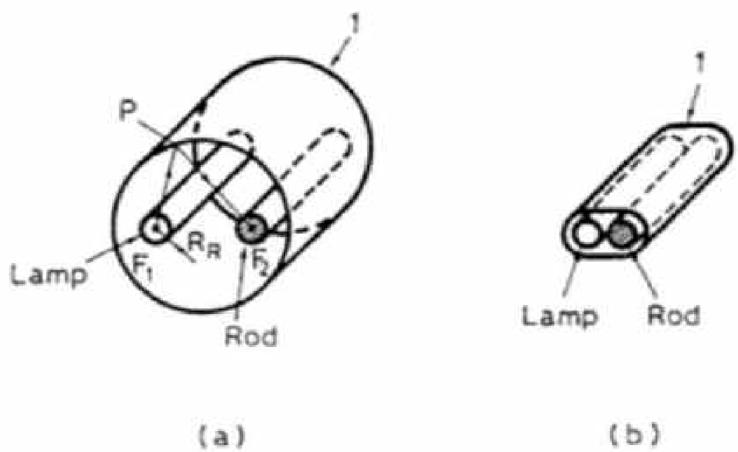


2 In optical pumping, a lamp alongside the laser rod creates the population inversion. The elliptical pump cavity focuses rays from the lamp into the rod.

The electromagnetic radiation source can be of different kinds:

- ***Flash lamps**, which are build from a quartz tube filled with gas at low pressure. Usually **Xenon gas**, **Krypton** or **Helium** are used.*
- ***Another laser** or **any other light source**.*

Draw different geometry of optical pumping and mention the useful of each one!!



Pump configurations using one lamp: (a) elliptical cylinder; (b) close-coupling.

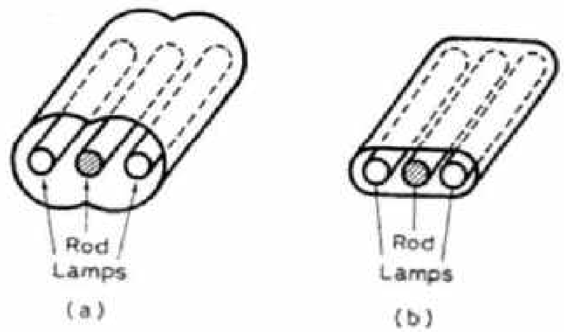


FIG. 6.2. Pump configurations using two lamps: (a) double-ellipse; (b) close-coupling.

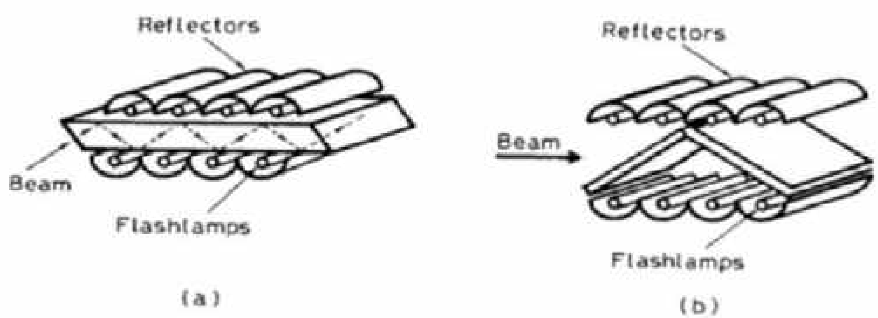


FIG. 6.3. Pumping configuration using many lamps: (a) Active medium in the form of a single slab with the laser beam traversing the slab in a zig-zag path. (b) Active medium made of many slabs inclined at Brewster's angle to the laser beam.

3- chemical pumping :-

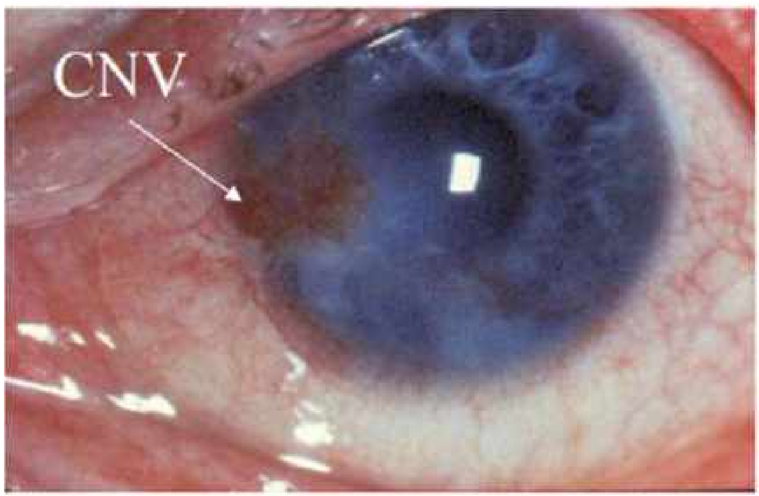
It is a method used during reaction between chemical materials , and as result the reaction producing a new chemical material in exited state for example fluoride laser

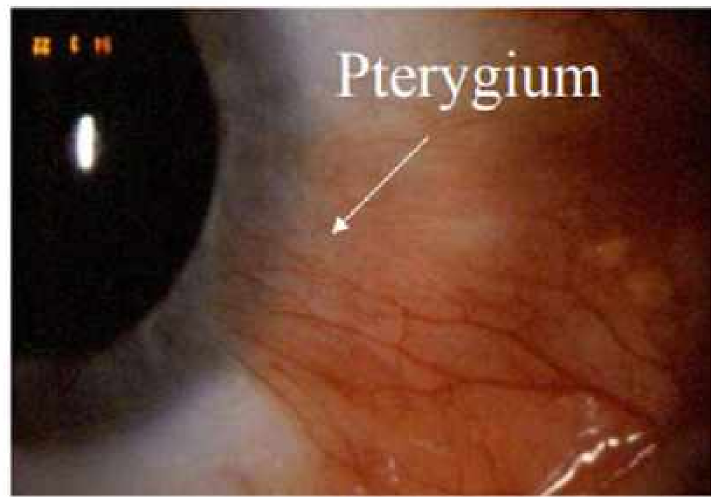
$$H_2 + F_2 \longrightarrow 2(HF)$$

Chemical lasers are not very common but because they're capable of extremely high powers, they've been developed in the past by the military for weapons applications

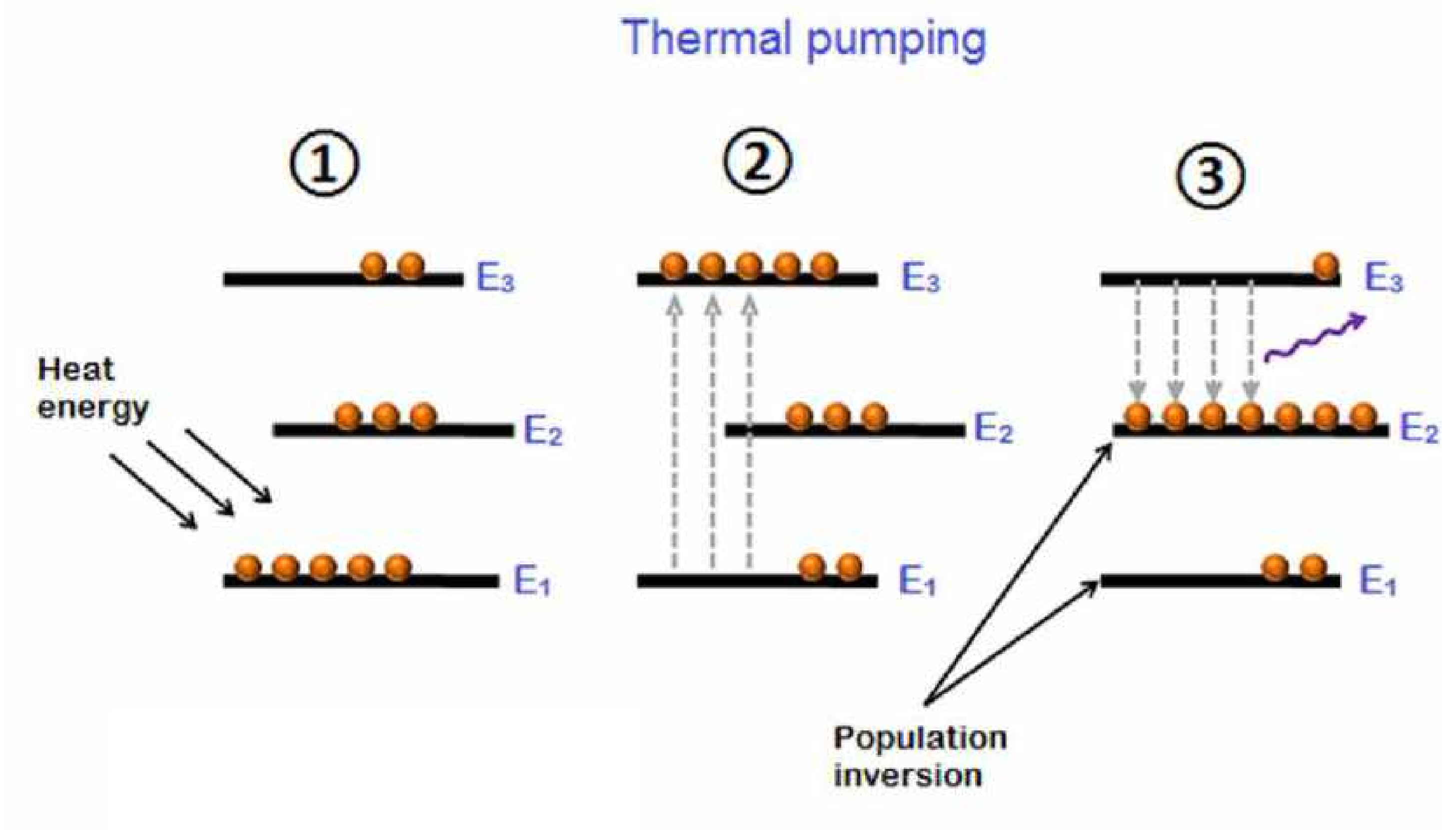
- An exotic pumping mechanism should be mentioned here also, for the sake of completeness. Lasers have been pumped by nuclear particles, usually from nuclear bombs. The energy in the particles creates a population inversion in the laser medium, and a pulse of laser output is obtained before the shock wave and other energy from the bomb destroys the laser. Such lasers may someday have military applications. Finally, free-electron lasers are pumped by high-energy electrons. The output of a free-electron laser is produced from electrons that are free rather than

bound to an atom or molecule. Thus, the physics of a free-electron laser is much different from that of other lasers. ***Free electrons have no fixed energy levels like bound electrons, so the laser's wavelength can be tuned.*** *Although free-electron lasers are promising for future applications, they are highly experimental and have been operated in only a few laboratories worldwide.*





4- thermal pumping



X-ray pumping?

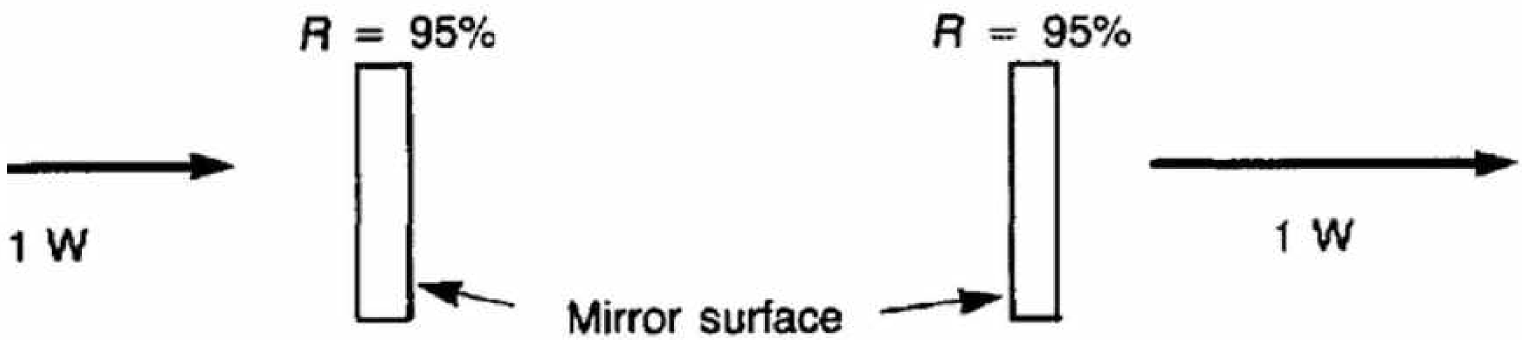
-Fabry - Perot interferometer

The main principle of Fabry Perot Etalon is light is passed through a pair Of parallel , highly reflecting etalon.
Interference between components of light undergoing *multiple reflections* result in extremely well defined inference fringes .

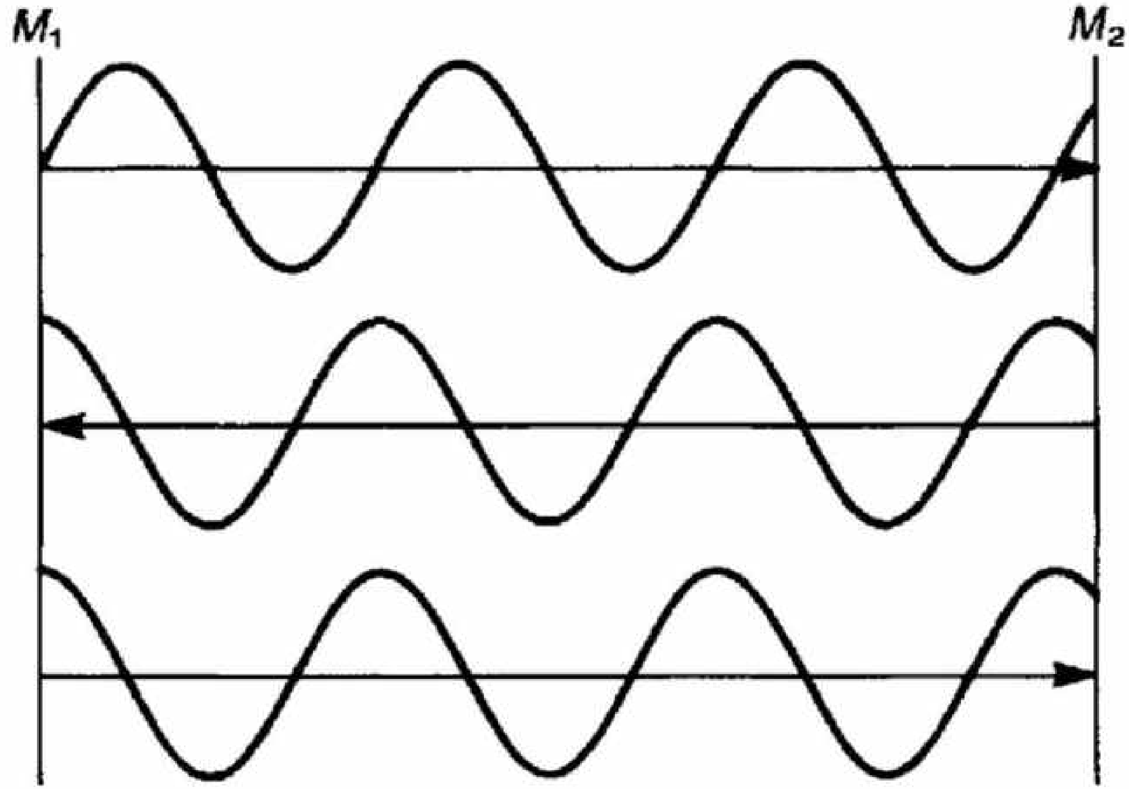
Charles Fabry

Alfred Perot

It is named after Charles Fabry and Alfred Perot. "Etalon" is from the French étalon, meaning "measuring gauge" or "standard".



0 If a Fabry-Perot interferometer is resonant, it will transmit all the incident light, no matter how great the reflectivity of the individual mirrors.



A nonresonant Fabry-Perot.

$$L = n\frac{\lambda}{2}$$

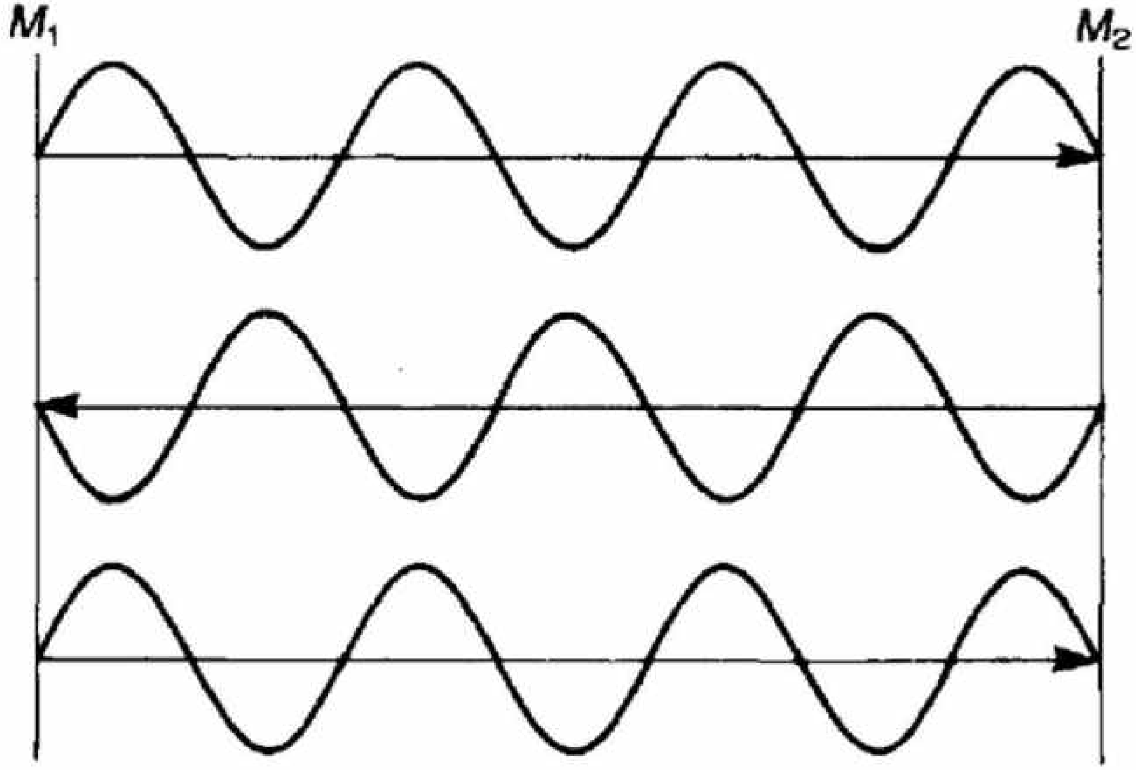
$$\lambda = \frac{c}{f}$$

$$f = \frac{nC}{2L}$$

$$f(n) = \frac{nc}{2L}$$

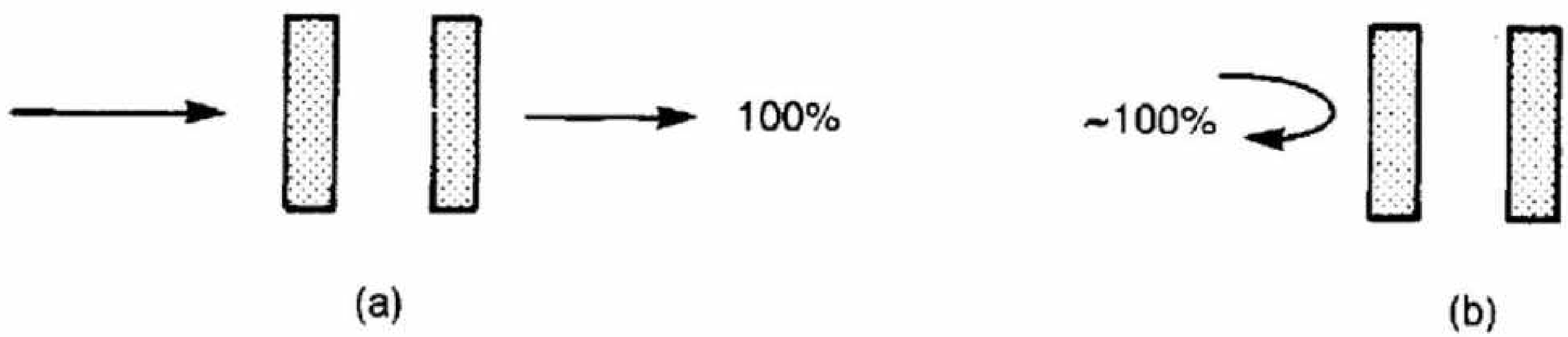
$$f(n+1) = \frac{(n+1)c}{2L}$$

$$\Delta f = f(n+1) - f(n) = \frac{c}{2L}$$



A resonant Fabry-Perot.

Figure below summarizes the behavior of a Fabry-Perot interferometer. If the interferometer is resonant (i.e., if the spacing between its mirrors is equal to an integral number of half-wavelengths of the incident light), it will transmit the incident light, no matter how great the reflectivities of the individual mirrors. If the interferometer is nonresonant, it will reflect almost all the incident light (assuming that the mirrors are highly reflective).

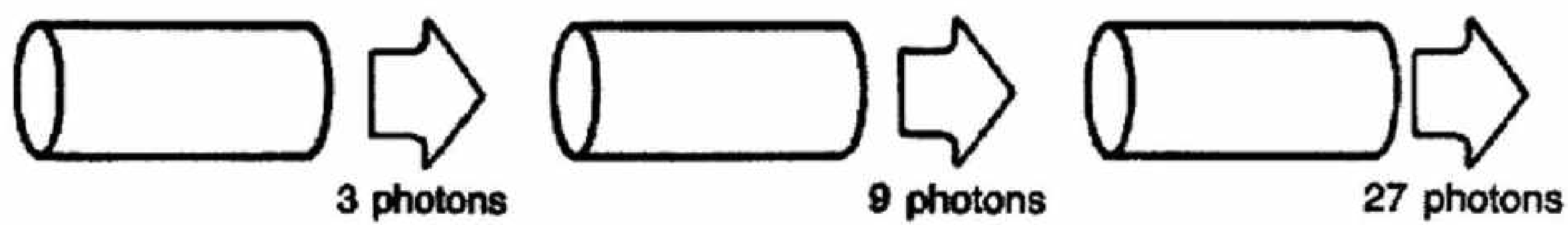


Almost all the incident light is transmitted through a resonant Fabry-Perot (a) and almost all the incident light is reflected from a nonresonant Fabry-Perot (b).

Resonator :-

WHY A RESONATOR?

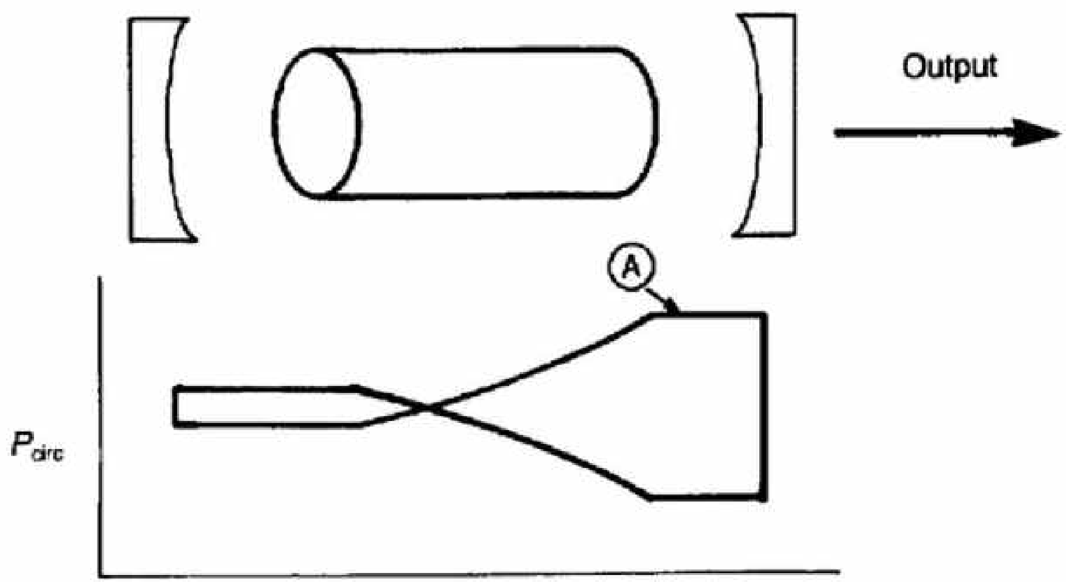
Let's think about what kind of a laser you might have with just a population inversion and nothing else—specifically, no resonator. Suppose that you created a big population inversion in a laser rod, and suppose that one of the atoms at the far end of the rod spontaneously emitted a photon along the axis of the rod. The photon might stimulate another atom to emit a second photon, and, since we're assuming a big population inversion, one of these two photons might even find a third excited atom and create another stimulated photon. Thus, screaming out the near end of the laser rod come . . . three photons.



How to make a laser without a resonator.

CIRCULATING POWER:-

If the photons in Fig below bounce back and forth between the mirrors for a long enough period, the laser will reach a steady-state condition and a relatively constant power will circulate between the mirrors. This circulating power is not absolutely constant, as indicated in Fig below Part of it is lost when it hits the output mirror, and this lost power is replaced when the light passes through the gain medium.



A schematic representation of the circulating power inside a laser resonator; the lower drawing shows the power in the resonator.

You can follow it around, starting, for example, at point A and moving to the right. The circulating power drops at the output mirrors because part of the light is transmitted through the mirror. The remaining light travels through the gain medium, where it is partially replenished. There's a small loss at the back mirror because no mirror is a perfect reflector. Then the light returns for a second pass through the gain medium, where it is fully restored to its previous level at point A.

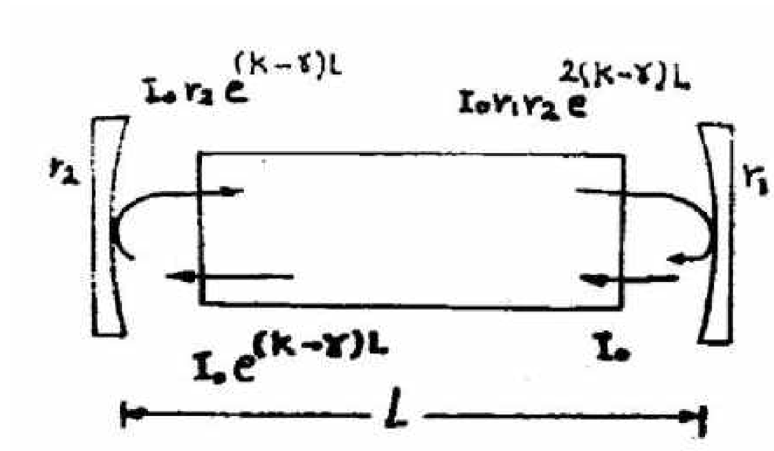
$$P_{\text{out}} = \tau P_{\text{circ}}$$

Gain and loss:-

What are the causes of loss inside a laser resonator?

Obviously, the transmission of the output mirror is one source of loss, but some circulating power is also lost at every optical surface in the resonator because there's no such thing as a perfect surface. Some light will be scattered and reflected no matter how well the surface is polished. As we've said, some light is lost at the imperfect rear mirror. Other light is lost by scattering as it propagates through refractive-index in homogeneities in the gain medium. Some loss by diffraction occurs because of the finite aperture of the laser beam inside the resonator.

$I = I_0 \; e^{(k-\gamma)L}$



$$I = I_o r_1 r_2 e^{2(k-\gamma)L}$$

$$G = \frac{I_o r_1 r_2 e^{2(k-\gamma)L}}{I_o}$$

$$G = r_1 r_2 e^{2(k-\gamma)L}$$

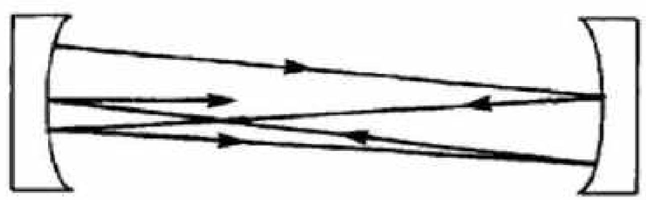
G=1 at threshold gain

$$1 = r_1 r_2 \, e^{2(k_{\,th}-\gamma)L} \rightarrow \frac{1}{r_1 r_2} = e^{\,2(k\,th-\gamma)L}$$

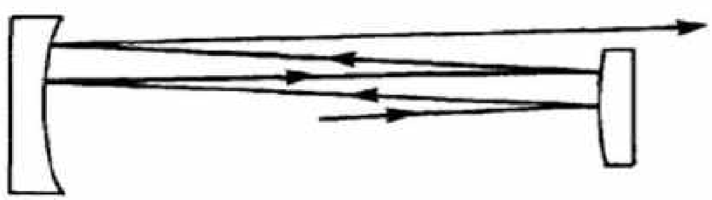
$$K_{th} = \gamma + \frac{1}{2L} \ln\left(\frac{1}{r_1 r_2}\right)$$

UNSTABLE RESONATORS

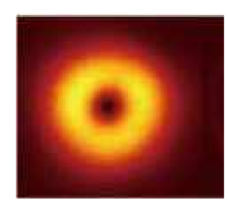
In the unstable resonator diagrammed in Figure below , the light rays continue to move away from the resonator axis until eventually they miss the small convex mirror altogether. The output beam from this resonator will have a doughnut-like shape with a hole in the middle caused by the shadow of the small mirror



A ray is always reflected back toward the center by the curved mirrors of a stable resonator.



In this unstable resonator, a ray will eventually be reflected past one of the mirror.



LASER MIRRORS:-

Laser mirrors are different from bathroom mirrors. As you probably know, an ordinary bathroom mirror is fabricated by depositing a metallic surface on the back of a piece of glass. Although metal mirrors are sometimes used in very high-power lasers, most laser mirrors are dielectric mirrors. They are made by depositing alternate layers of high- and low-index materials on a substrate.

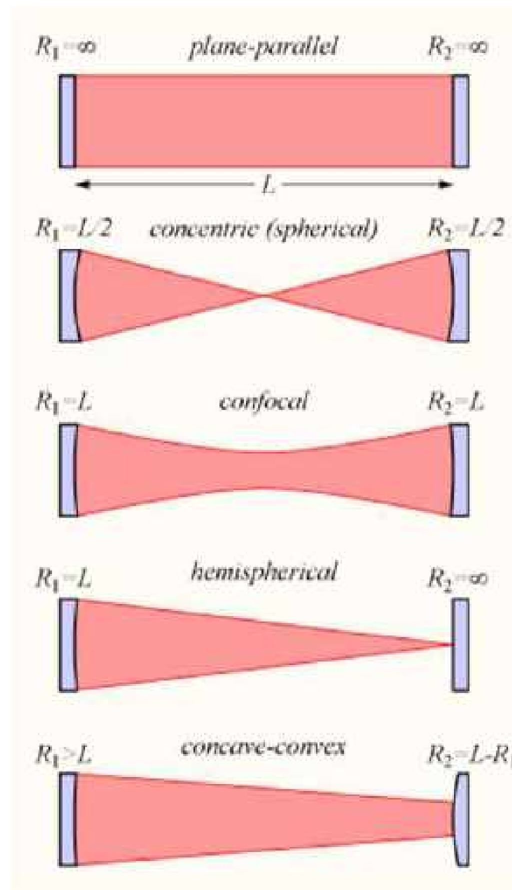
A fraction of the incident light is reflected from each interface, and the total reflectivity depends on the relative phase of these reflections. A high-reflectivity mirror, for example, might have several layers of transparent material deposited on a glass substrate. Each layer would be exactly the right thickness so that the light reflected from its front surface would be precisely in phase with the light reflected from its rear surface. It is possible to fabricate dielectric mirrors like this whose reflectivity is greater than 99.9999%.

Resonator types

Various types of optical resonators

The cavity is designed so that the beam will remain entirely within the cavity's mirrors. These are referred to as follows where R1 and R2 are the radii of curvature of the mirrors and L is the distance between the mirrors:

a) plane-parallel	$R_1=R_2=\infty$
b) concentric (spherical)	$R_1+R_2=L$
c) confocal	$R_1+R_2=2L$
d) hemispherical	$R_1=L,\ R_2=\infty$
e) concave-convex	$R_1>>L,\ R_2=L-R_1$



There are simple mathematical formulae that indicate whether or not a cavity is stable. In its simplest form, the rule can be stated as follows: Given a cavity made of two spherical mirrors (of radii of curvature R_1 and R_2) separated by a distance L, the cavity is stable if

$$0 \leq g_1 g_2 \leq 1$$

Where:

$$g_1 = 1 - \frac{L}{R_1}$$

$$g_2 = 1 - \frac{L}{R_2}$$

If g_1 and g_2 are such that their intersection lies within the shaded region of this diagram, then the cavity is stable