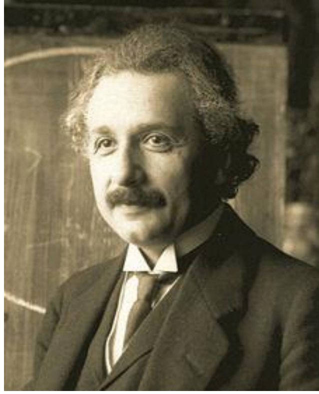
1.3	Principles of lasers: Interaction of radiation with matter, population, pumping, active medium, optical resonator, Einstein's coefficients, population inversion, threshold condition, laser beam parameters

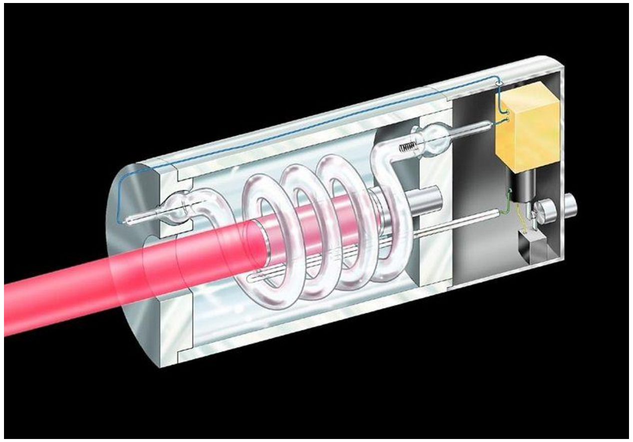
A short sketch of laser history



1917: Einstein – stimulated absorption and emission of light

1954: Charles Townes and Schawlow – maser, prediction of the optical laser Nobel Prize (1964)

1960: Theodore Maiman – first demonstration of a laser: Ruby laser



Rapid progress in the 1960s:

- 1961: first gas laser, first Nd laser
- 1962: first semiconductor laser
- 1963: CO_2 laser (IR)

Definition of LASER

- The acronym LASER stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.
- A laser is a device that generates light by a process called **STIMULATED EMISSION**.
- In 1960, T. H. Maiman built the first laser device (ruby laser)

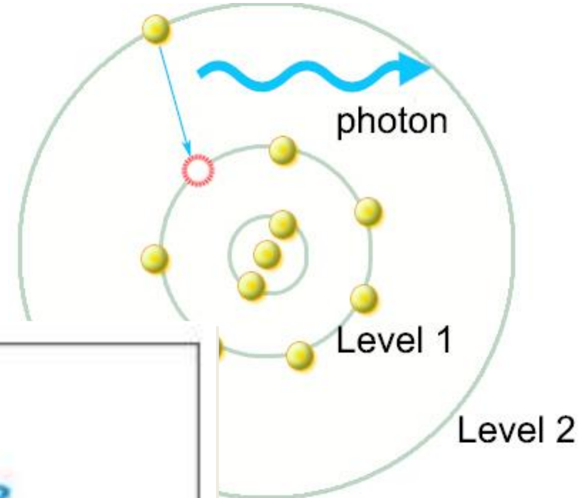
Properties of Laser

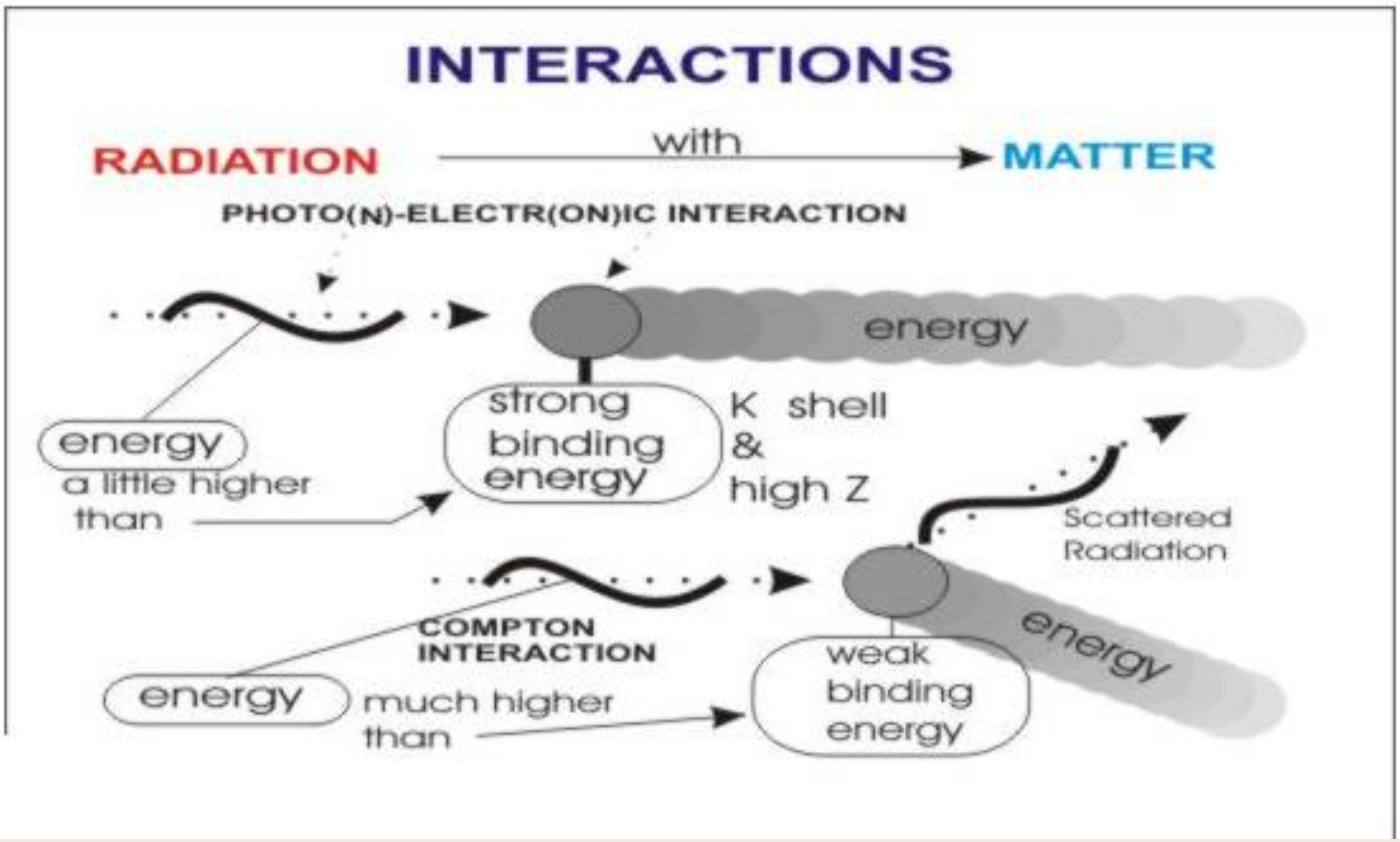
- The light emitted from a laser is **monochromatic**, that is, it is of one color/wavelength. In contrast, ordinary white light is a combination of many colors (or wavelengths) of light.

- 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. Ordinary light can be a mixture of many wavelengths.

These three properties of laser light are what can make it more hazardous than ordinary light. Laser light can deposit a lot of energy within a small area.


photon
Level 1
Level 2

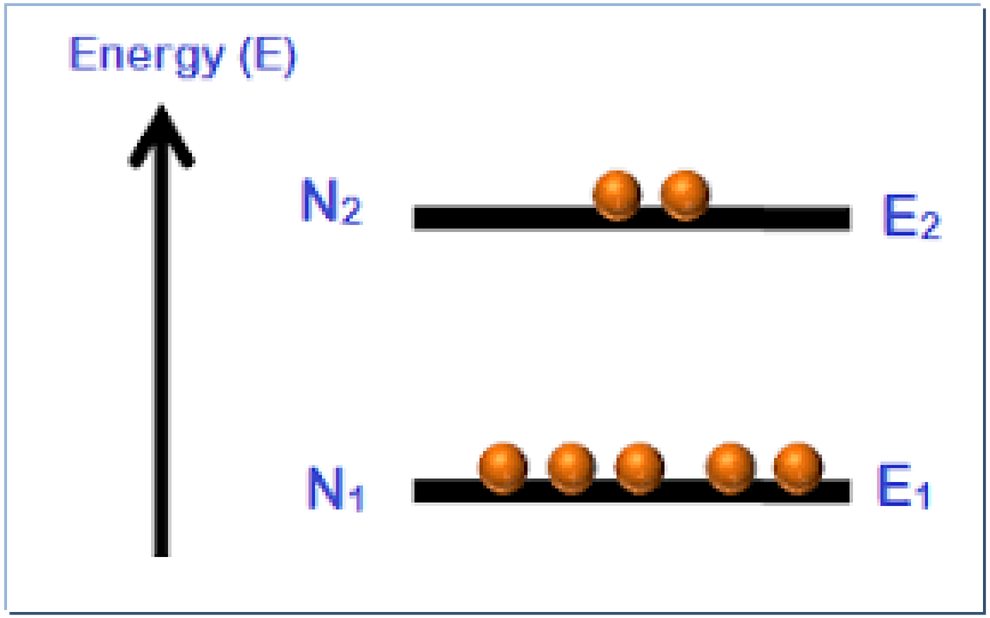

INTERACTIONS
RADIATION
with
MATTER
PHOTO(N)-ELECTR(ON)IC INTERACTION
energy
energy
a little higher
than
strong
binding
energy
K shell
&
high Z
Scattered
Radiation
COMPTON
INTERACTION
energy
energy
much higher
than
weak
binding
energy

Basic concepts for a laser

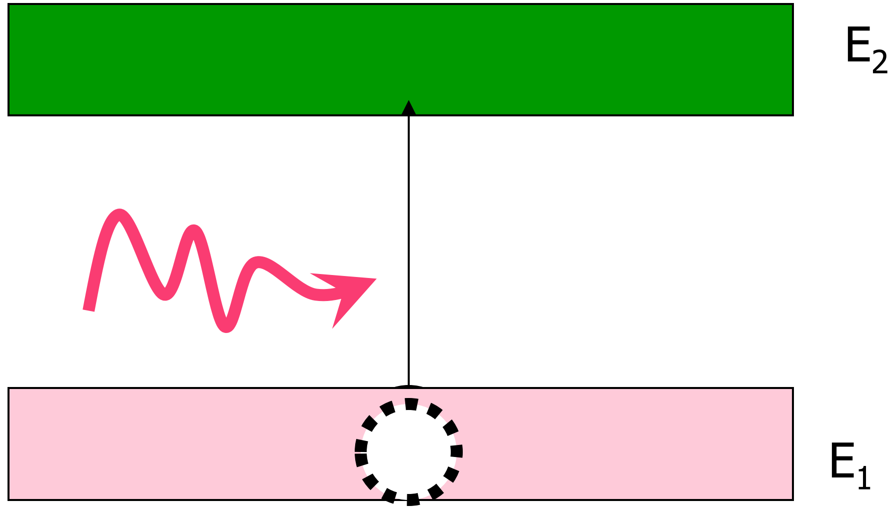
- **Population**
- **Absorption**
- **Spontaneous Emission**
- **Stimulated Emission**
- **Population Inversion**
- **Pumping**
- **Active medium**
- **Resonance Cavity**

Population

The number of atoms in a particular energy level is called population.



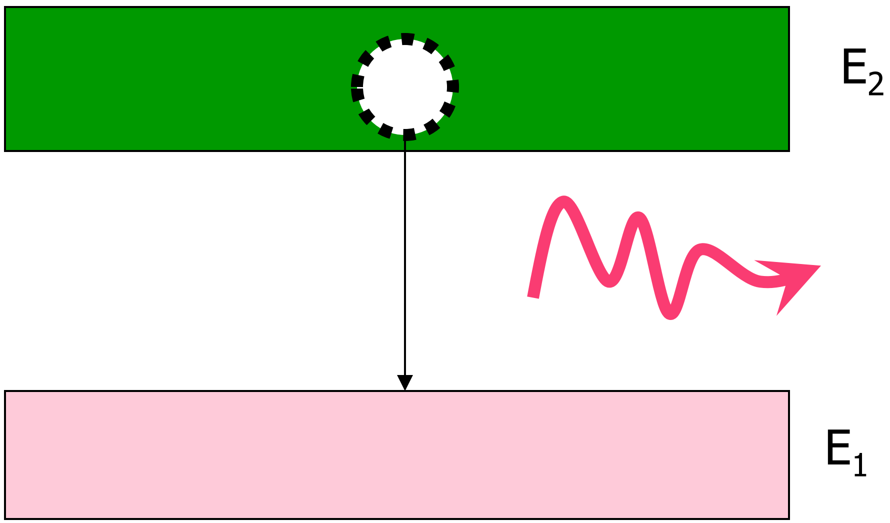
Absorption



Corresponding to each transition from E_1 to E_2, photon of energy $h\nu = E_2 - E_1$ is absorbed and the atom is excited.

The number of atoms excited during time Δt is, $N_{ab} = B_{12}N_1Q\Delta t$

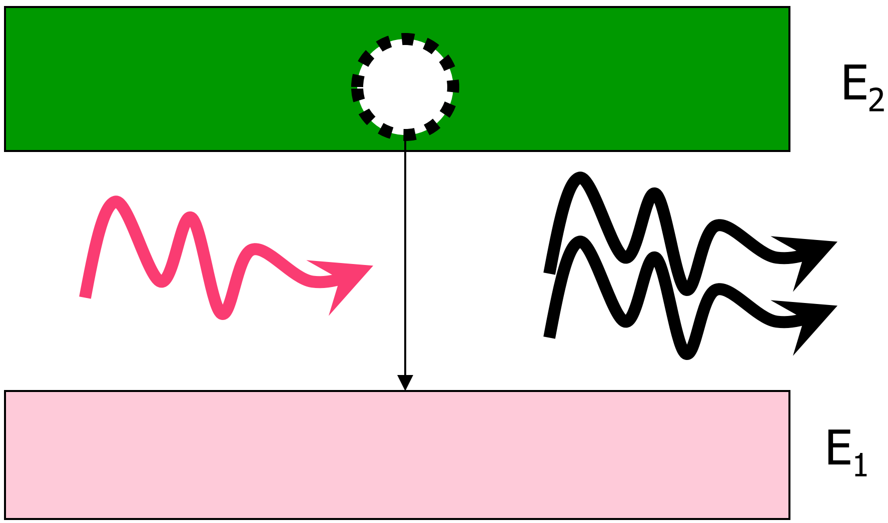
Spontaneous Emission



Corresponding to each transition from E_2 to E_1, photon of energy $h\nu = E_2 - E_1$ is emitted.

The number of atoms de-excited during time Δt by spontaneous emission is, $N_{sp} = A_{21}N_2\Delta t$

Stimulated Emission



Corresponding to every transition from E_2 to E_1 , two identical photons of energy $h\nu = E_2 – E_1$ are emitted.

The number of atoms de-excited during time Δt by stimulated emission is, $N_{st} = B_{21}N_2Q\Delta t$.

Advantages of stimulated emission over spontaneous emission

(a) The process is controllable from outside.

(b) The induced radiation is identical to the incident radiation.

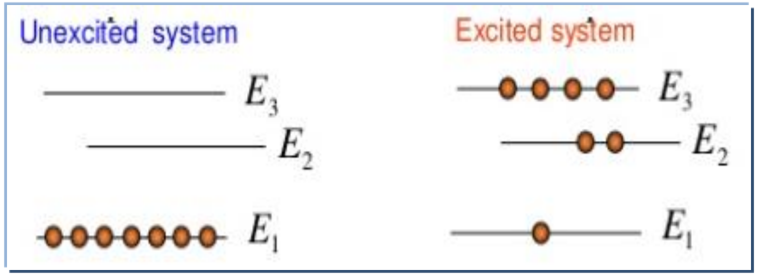
(c) By selecting proper active medium and resonance conditions, light amplification can be achieved.

(d) As a result, we get a highly monochromatic, coherent, directional, focused and intense radiation.

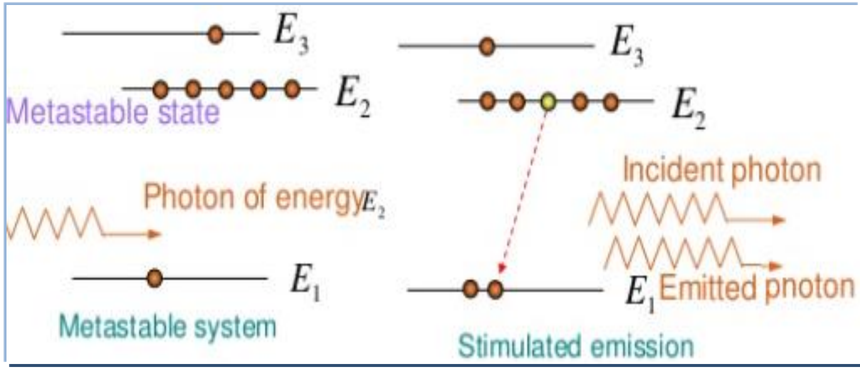
INVERTED POPULATION or POPULATION INVERSION

When a sizable population of electrons resides in upper levels, this condition is called a "population inversion"
In order to obtain the coherent light from stimulated emission, two conditions must be satisfied:

1. The atoms must be excited to the higher state. That is, an inverted population is needed, one in which more atoms are in the upper state than in the lower one, so that emission of photons will dominate over absorption.



2. The higher state must be a metastable state – a state in which the electrons remain longer than usual so that the transition to the lower state occurs by stimulated emission rather than spontaneously.



Pumping

A process of supplying energy to transfer atoms from lower energy state to higher energy state is called pumping.

A process of supplying energy to get population inversion is called pumping.

Pumping can be

Optical: flashlamps and high-energy light sources

Electrical: application of a potential difference across the laser medium etc

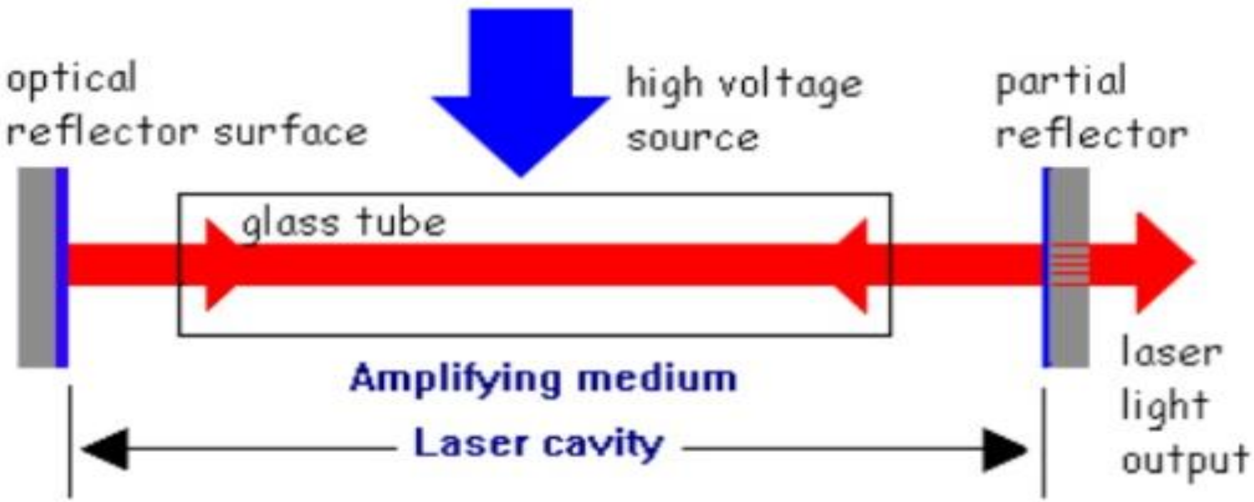
Active medium

The medium in which population inversion is possible is called active medium .

The active medium can be solid, liquid or gas.
The **active medium** is a collection of atoms or molecules, which can be excited into a population inversion situation.

The atoms of active medium are called active atoms or active centres.

Optical Resonator



- the beam of light is reflected back and forth along the central tube, until the waves of light become coherent.

An optical resonator or optical cavity or , resonating cavity is an arrangement of mirrors that forms a standing wave cavity resonator for light waves.

ACTIVE MEDIUM

Solid (Crystal)
Gas
Semiconductor (Diode)
Liquid (Dye)

The **Active Medium** contains atoms which can emit light by stimulated emission.

EXCITATION MECHANISM
or
PUMPING

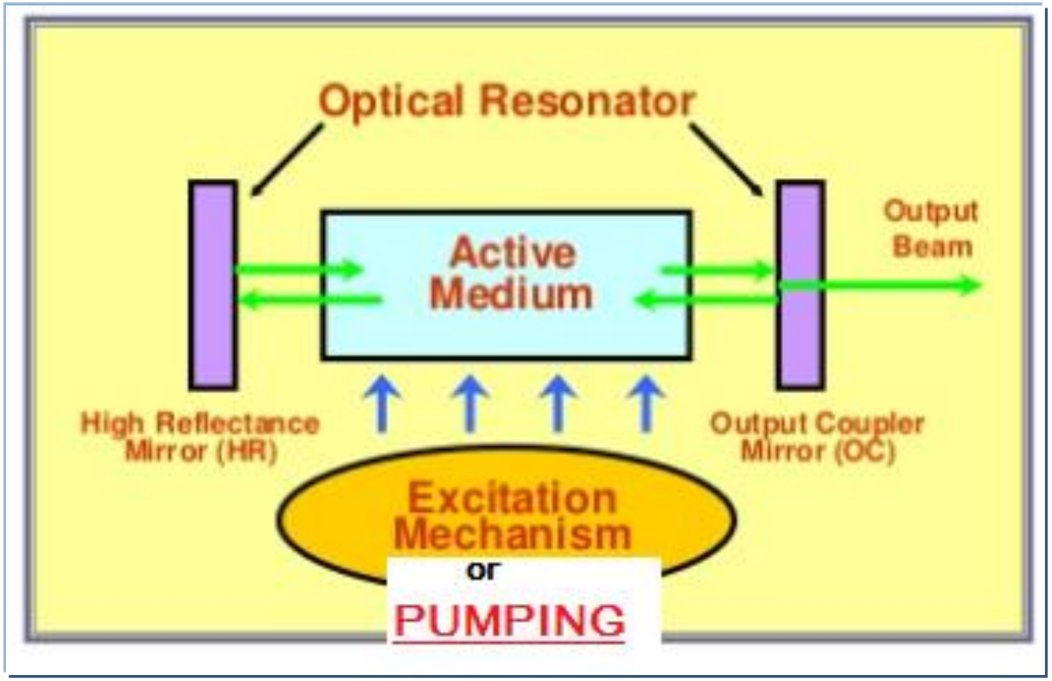
Optical
Electrical
Chemical

The **Excitation Mechanism** is a source of energy to excite the atoms to the proper energy state.

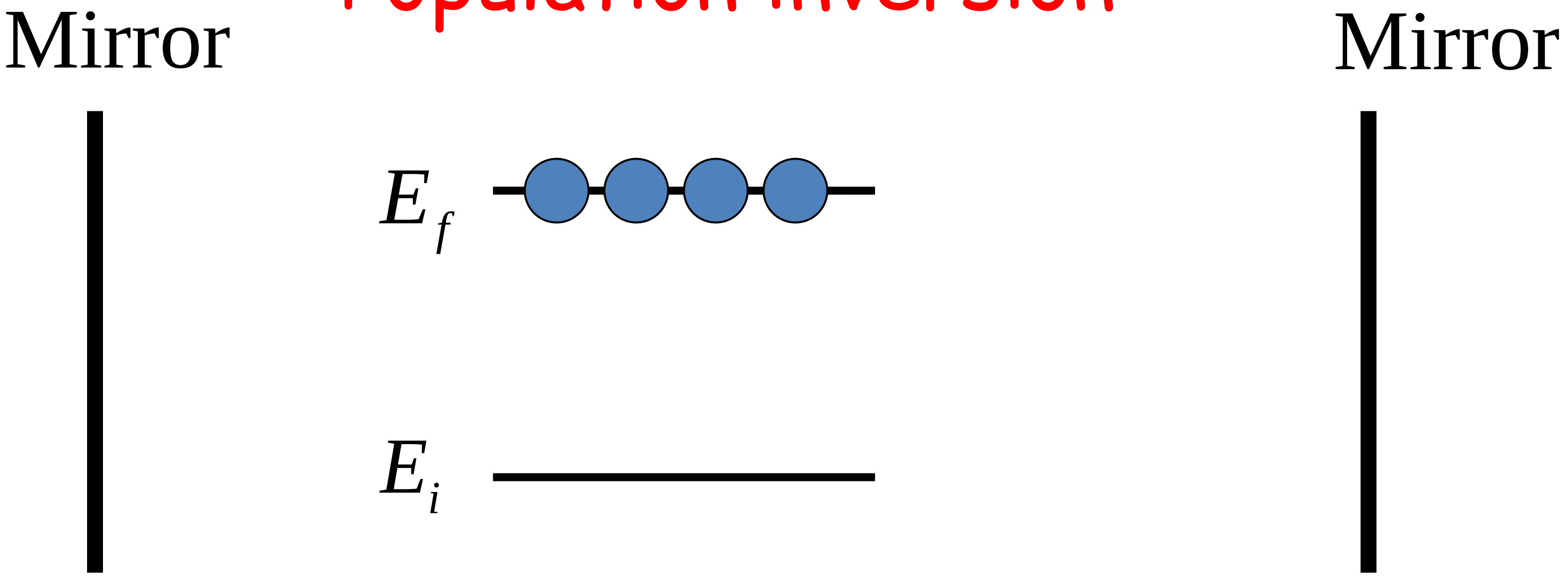
OPTICAL RESONATOR

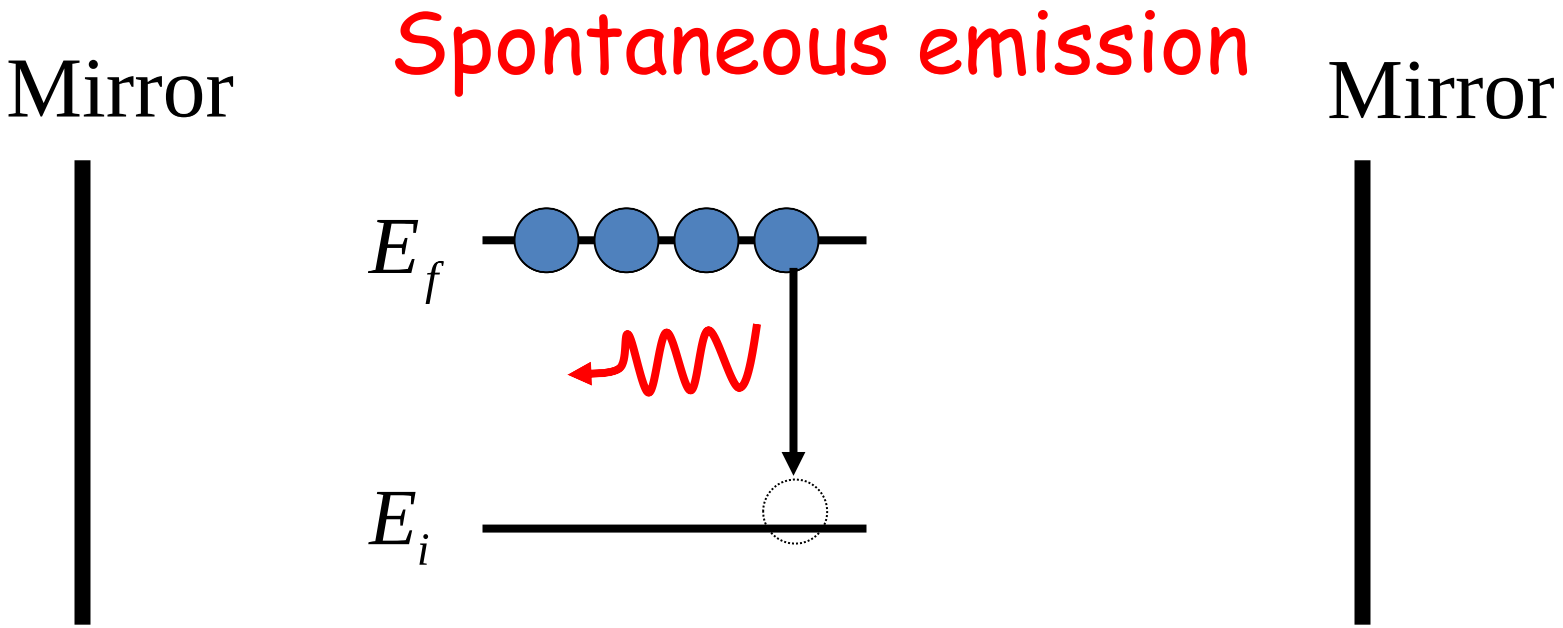
HR Mirror and
Output Coupler

The **Optical Resonator** reflects the laser beam through the active medium for amplification.



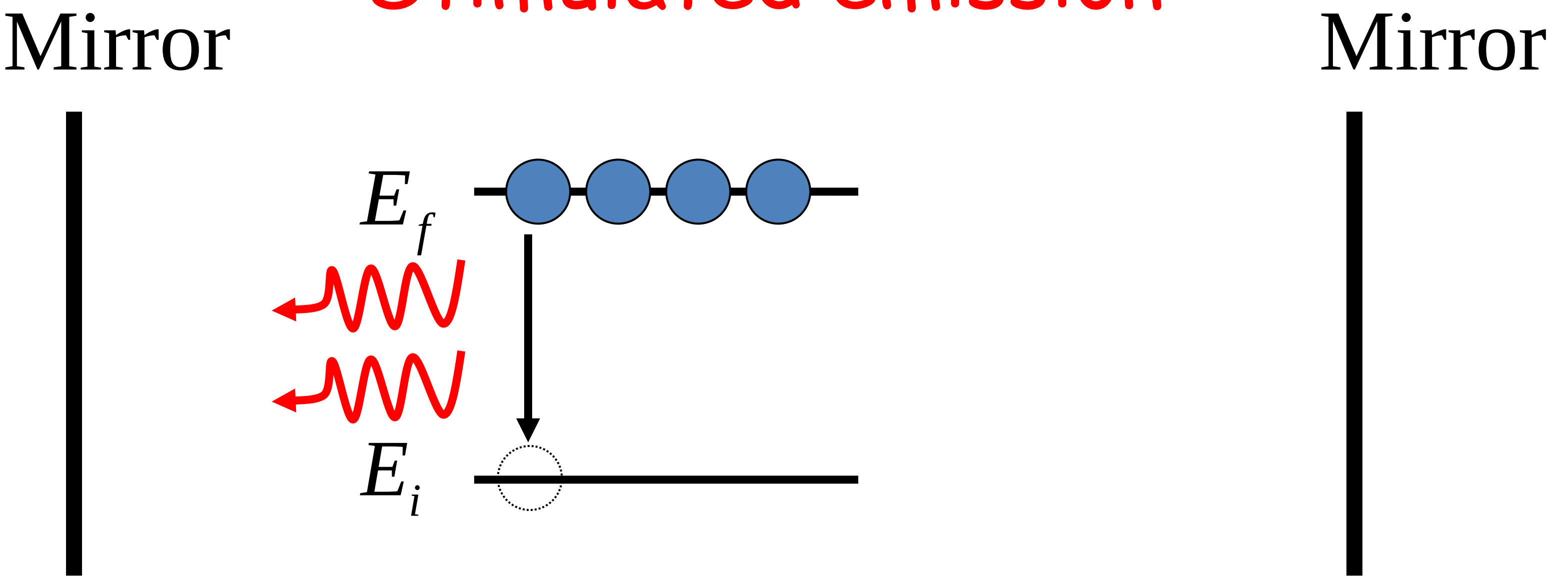
Population inversion



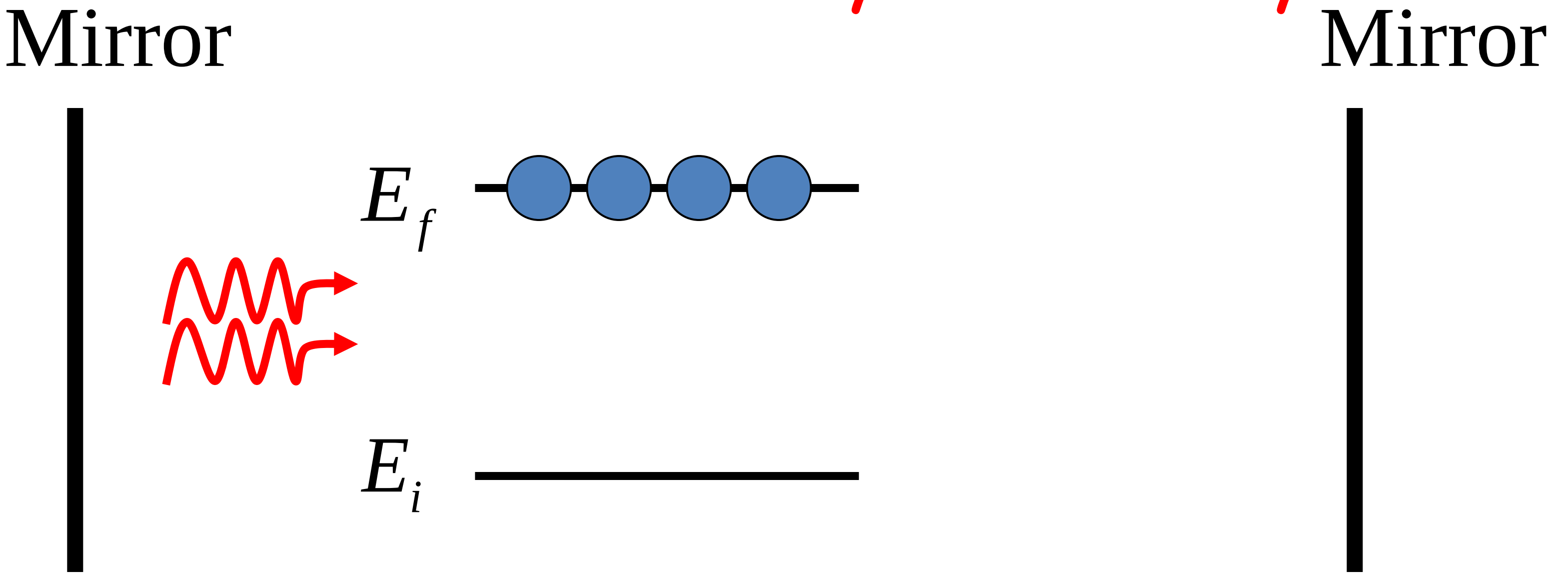


Spontaneous emission
Mirror
Mirror
E_f
E_i

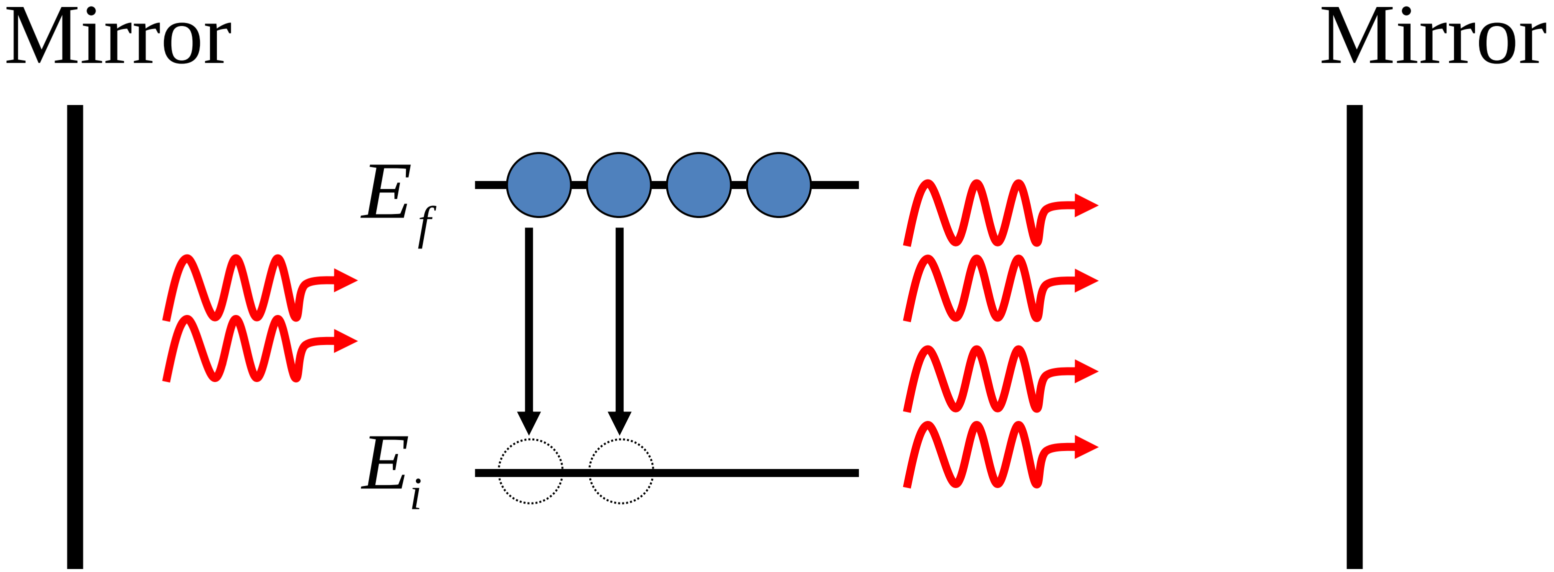
Stimulated emission



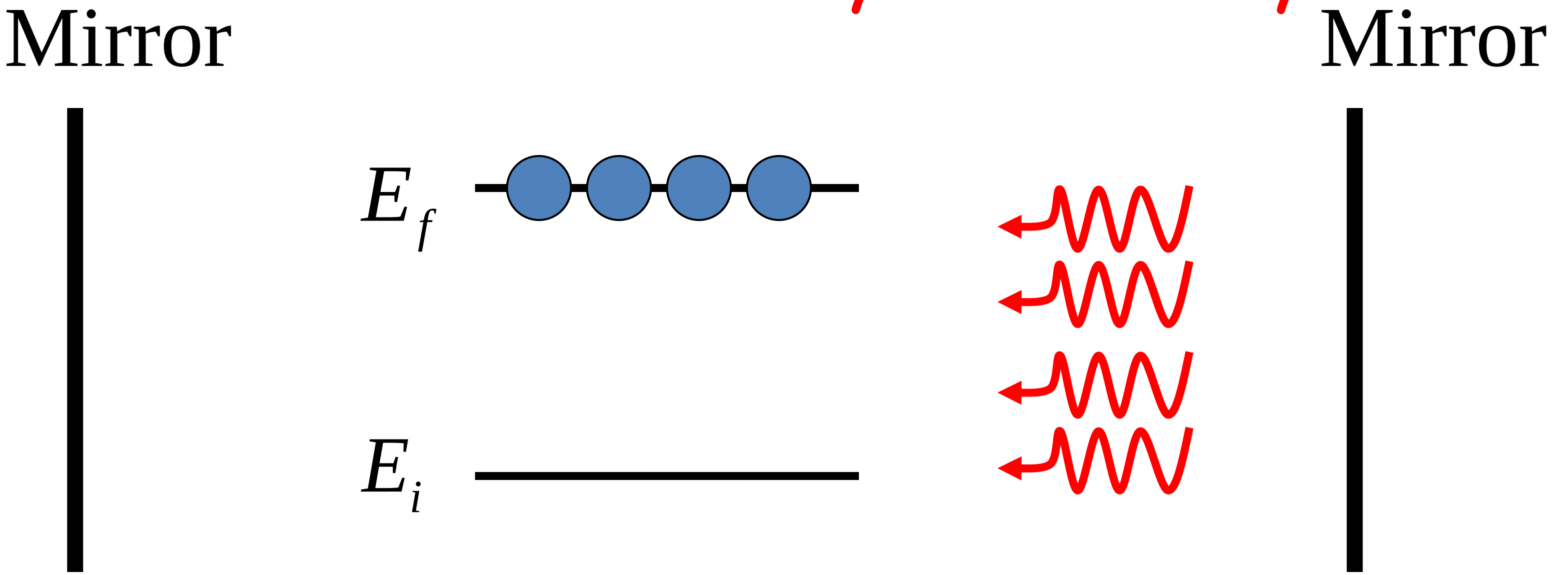
Feed-back by the cavity



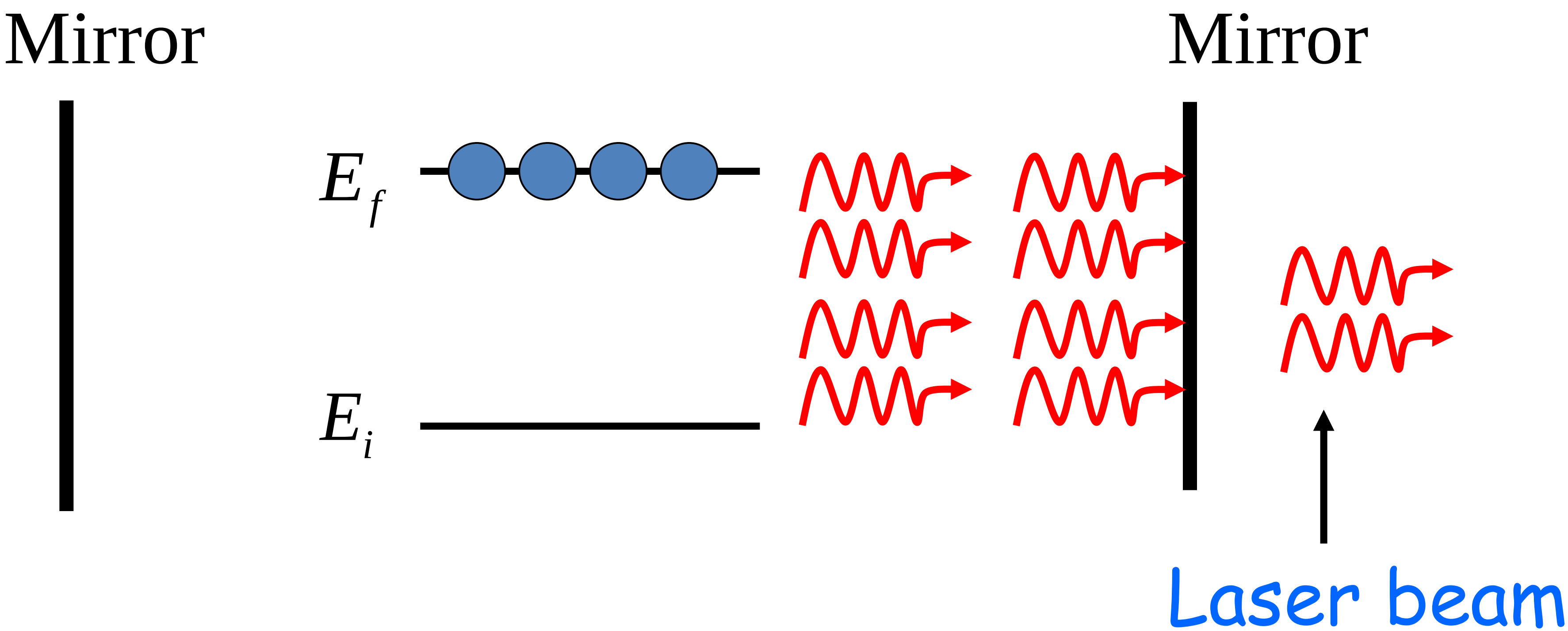
Stimulated emission



Feed-back by the cavity



After several round trips…



Photons with:

- **same energy : Monochromatic**
- **same direction of propagation : Spatial coherence**
- **all in synchrony: Temporal coherence**

Einstein A and B coefficients

1. Consider a radiation field and a collection of two-level systems.

2. Stimulated emission probability: proportional to the number of atoms in upper state N_2, and also to the number of photons $N_{st} = B_{21}N_2Q\Delta t$..........(1)

3. Spontaneous emission probability: proportional to N_2, but does not depend on the photon density! $N_{sp} = A_{21}N_2\Delta t$......................................(2)

4. Stimulated absorption probability: proportional to the number of atoms in lower state N_1 and also to the number of photons $N_{ab} = B_{12}N_1Q\Delta t$ ....(3)

5. In thermal equilibrium, the upward and downward transition rates must balance

$$N_{ab} = N_{st} + N_{sp} \quad \text{.................................(4)}$$

For detailed derivation refer class notes

Threshold condition for LASER

When the small-signal gain just equals the resonator losses then it is called threshold condition of a LASER.

When operation is well above the threshold, then power output is significant, power efficiency is good and stable, noise is low

A low threshold power requires low resonator losses and a high gain efficiency.

It is achieved using a small laser mode area in an efficient gain medium with limited emission bandwidth.

The optimization of the laser output power for a given pump power usually involves a compromise between high slope efficiency and low laser threshold.

Threshold Condition

As light bounces back and forth in an optical resonator ,it undergoes attenuation as it suffers various losses .The losses occur mainly due to transmission at the output mirror ,inner mirror and due to scattering and diffraction of the light within the active medium and some other processes, which in total can be called as the absorption losses .For maintaining the continuous oscillations in the resonator cavity it is essential that this attenuation should be overcome by amplification between two consecutive reflection .For this amplification energy can be taken from pumping source. A mathematical condition can be obtained by considering the change in the intensity of the beam of the light undergoing the round trip. In short threshold condition is condition required to sustain oscillations in an optical resonator. This condition is given as

$$\gamma \geq \alpha_s + \frac{1}{2L} \ln \frac{1}{R}$$

Where

γ = amplification of the laser will be dependent on how hard laser medium is pumped

α_s=All type of losses

L= Length of the resonator

$R=r_1r_2$ = Where r_1 and r_2 are the Reflectivities of the mirrors(Input and output)

For detailed derivation refer class notes

Laser Beam Parameters

- **Beam Diameter (Radius, Width):** The beam diameter (generally defined as twice the beam radius, is the most important propagation-related attribute of a laser beam.

- **Spatial Intensity Distribution (Beam Profile):** It incorporates all the mechanical, thermal and electromagnetic variables that created the beam.

- **Divergence:** The beam divergence of a laser beam is a measure for how fast the beam expands as it propagates in space.

- **Beam Quality Factor M^2 (Beam Parameter Product):** It describes the propagation of an arbitrary beam and derived from the uncertainty principle. M^2 is a measureable quantity in order to characterize real mixed-mode beams.