Lecture 11:
Principles of Laser

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Recap

- PolyMUMPs process
- Ledit software for polyMUMPs
- Doing various designs with Ledit

Today

- Laser fundamentals
- How various kinds of lasers work
- Some basics about laser optics

Motivation

- Why study lasers?? What is their importance??
- MEMS context??
- Other micromachining techniques: compared with laser.

Capabilities of various Micro-machining technologies

Technology / Feature Geometry	Minimum Feature Size/Feature Tolerance	Feature Positional Tolerance	Material Removal Rate	Materials
FIB 2D/3D	200 nm / 20 nm	100 nm	5 $\mu m^3/s$	Any
Micro-milling/Micro-turning 2D/3D	25 μm / 2 μm	3 μm	10,400 $\mu m^3/s$	PMMA, Al, Brass, mild steel
Excimer laser 2D/3D	6μm /submicron	submicron	40, 000$\mu m^3/s$	Polymers, ceramics, metals to a lesser degree
Femtosecond laser/ 2D/3D	1 μm / submicron	submicron	13,000 $\mu m^3/s$	Any
Micro-EDM (Sinker or wire) 2D / 3D	25 μm / 3 μm	3 μm	25 million $\mu m^3/s$	Conductive materials
LIGA / 2D	Sub micron / 0.02μm ~ 0.5 μm	~0.3 μm	NA	Cu, Ni, polymers, ceramics

Principles of Laser

- The word laser, actually an acronym for ***L***ight ***A***mplification by ***S***timulated ***E***mission of ***R***adiation, has become synonymous with everything that is high tech and futuristic.
- Lasers work on the central concept of converting electrical energy into a high energy density beam of light through stimulation and amplification.
- Light, radio waves, microwaves, X-rays and gamma rays are all electromagnetic waves.They differ only in their characteristic wavelength or frequency.

Principles of Laser

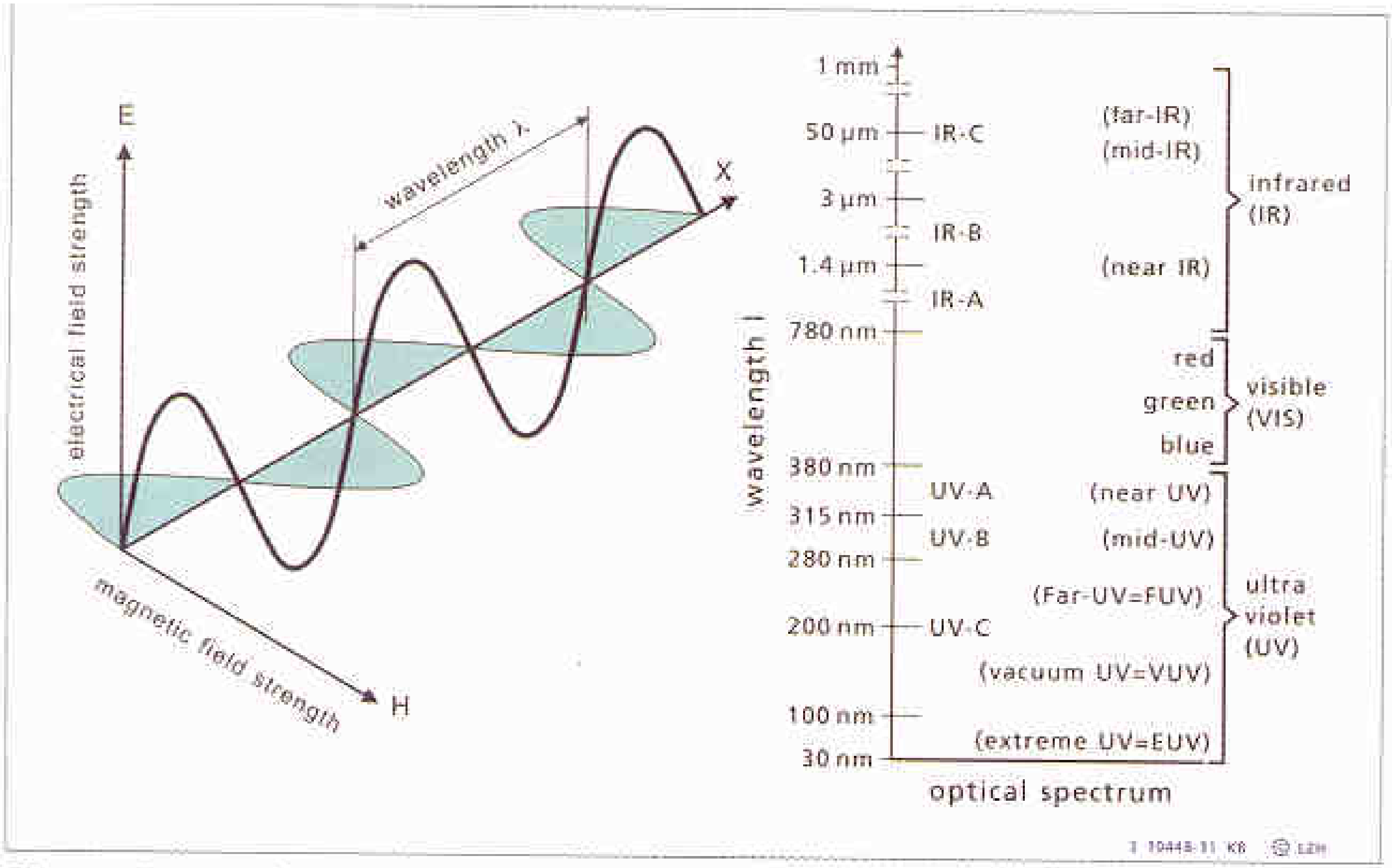
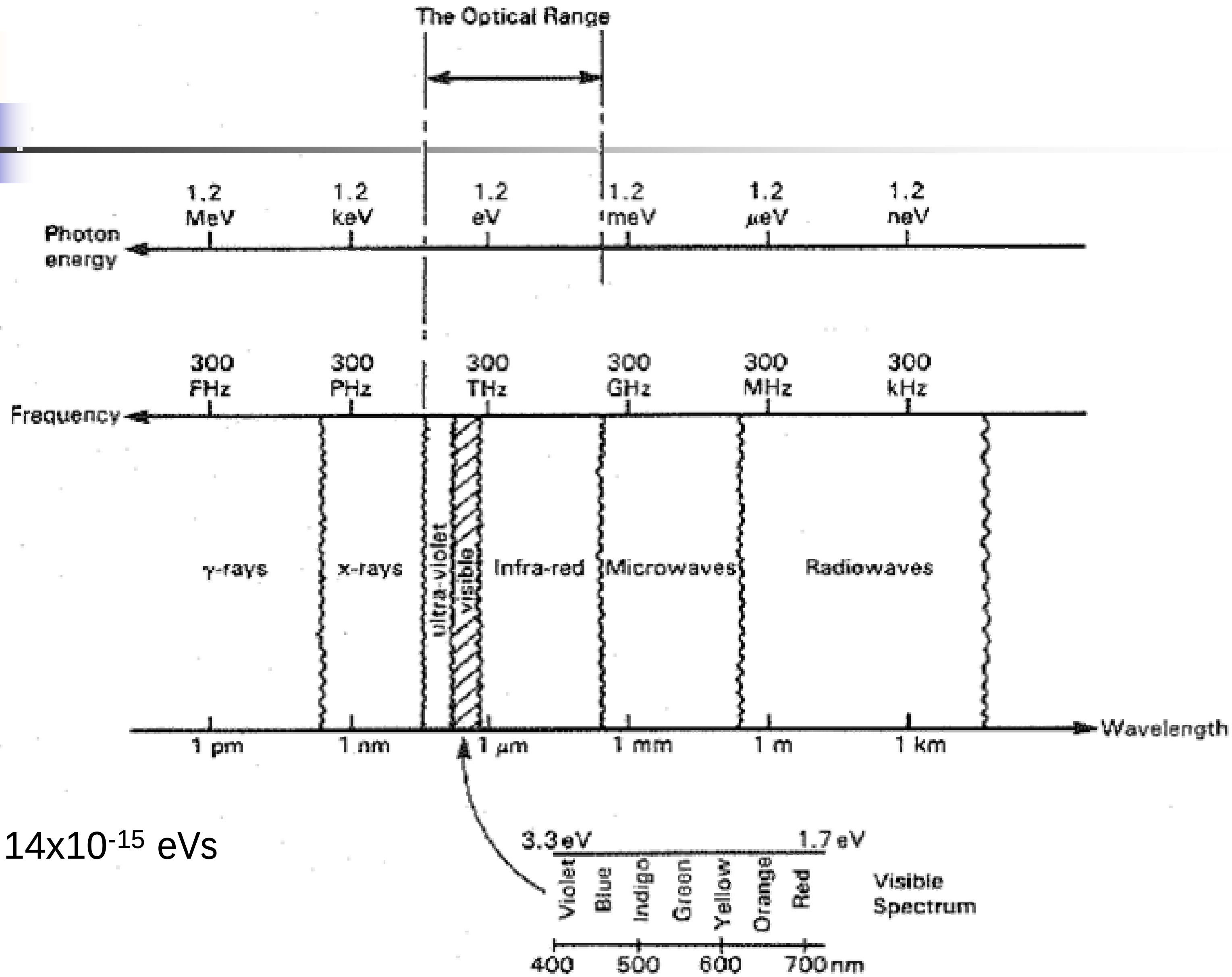


Figure 2.1-1: Electromagnetic wave and optical spectrum

Principles of Laser



$h=4.14\text{x}10^{-15}$ eVs

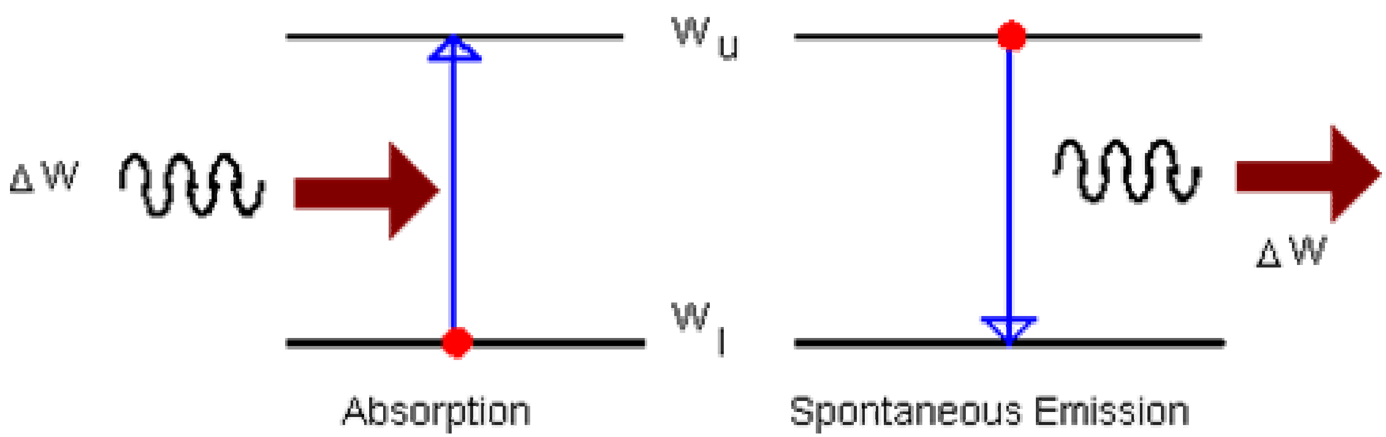
Principles of Laser

- Light is considered to stream of small lumps or QUANTA of energy, known as PHOTONS. Each photon carries with it a precisely defined amount of energy which depends upon its wavelength or frequency –

$$W_{ph} = hf = hc$$

where h is Planck's constant = $663x10^{-36}$ J s and c is the velocity of propagation of the photon in free space = $300x10^{6}$ m/s.

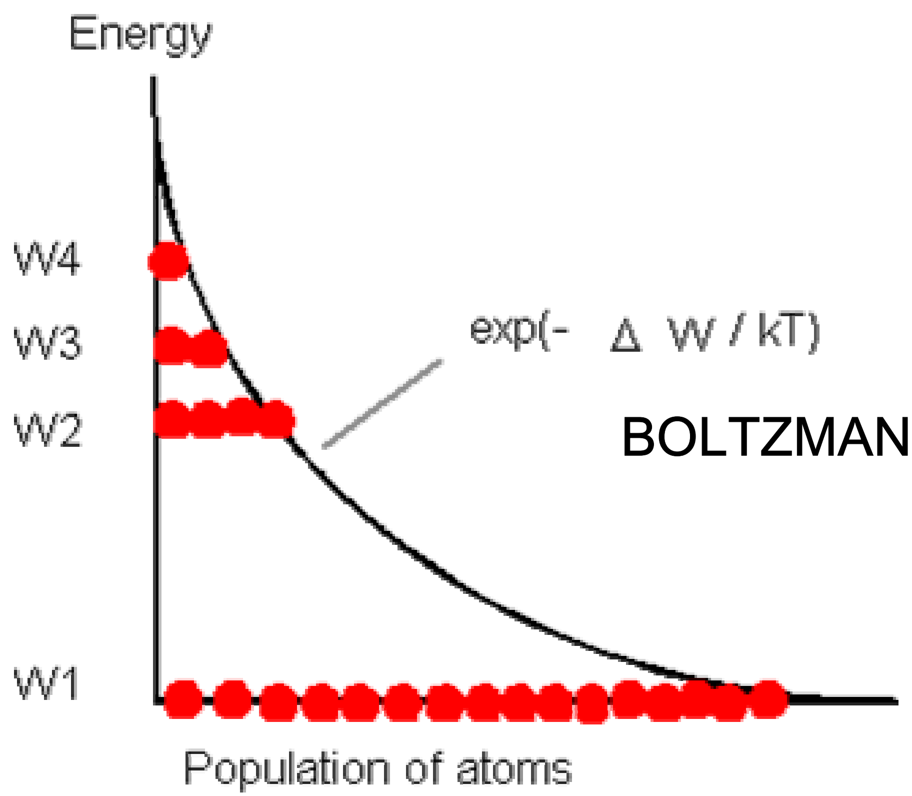
- Absorption and emission of light between atomic levels: The excited atom can SPONTANEOUSLY (randomly) de-excite to a lower level if a vacant site permits. The average length of time an atom stays in excited state is tens of nanoseconds



Principles of Laser

- **$W_{ph} = \Delta W = |W_u - W_l|$ PHOTON ENERGY**
- The population density of atoms, N_u, in an excited state, W_u, in relation to those, N_l, in a lower energy state W_l is given by the Boltzmann relationship, as,

$$N_u/N_l = \exp[-(W_u-W_l)/kT] = \exp[-W/kT]$$

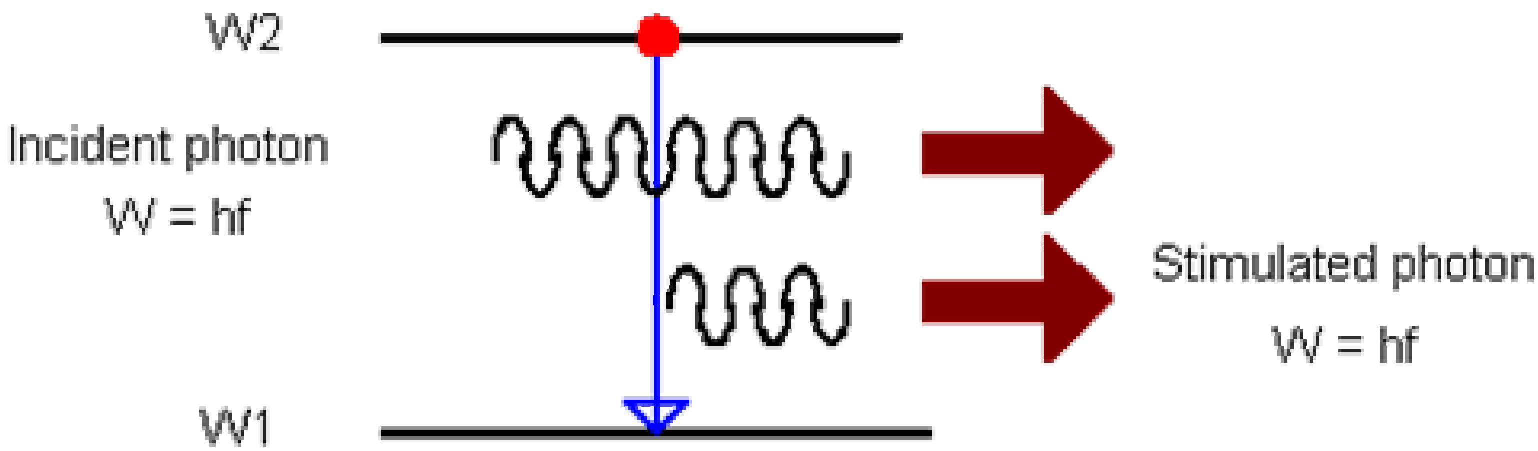


BOLTZMANN RELATIONSHIP

Principles of Laser

For atomic systems in thermal equilibrium with their surroundings, emission of light is the result of two main processes:

- ABSORPTION of energy
- SPONTANEOUS EMISSION of energy
- A third mechanism also exists: although not a dominant process in thermal systems at room temperatures, it is crucial to the formation of LASER action this process is known as STIMULATED EMISSION



Stimulated emission

Principles of Laser

•In stimulated emission, atoms in an upper energy level can be triggered or stimulated in phase by an incoming photon of a specific energy.

•Incident photon must have an energy corresponding to the energy difference between the upper and lower states and the incident photon is not absorbed by the atom.

•It actually vibrates the pair of energy levels with whom its energy coincides the atom de-excites with the consequent release of photons of the same energy as the incident photon.

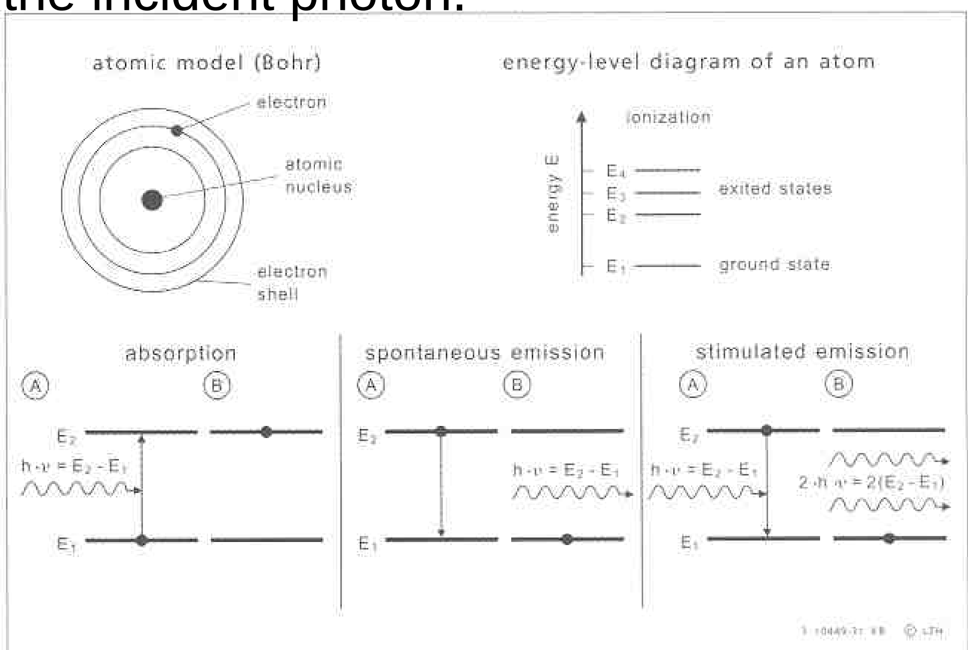


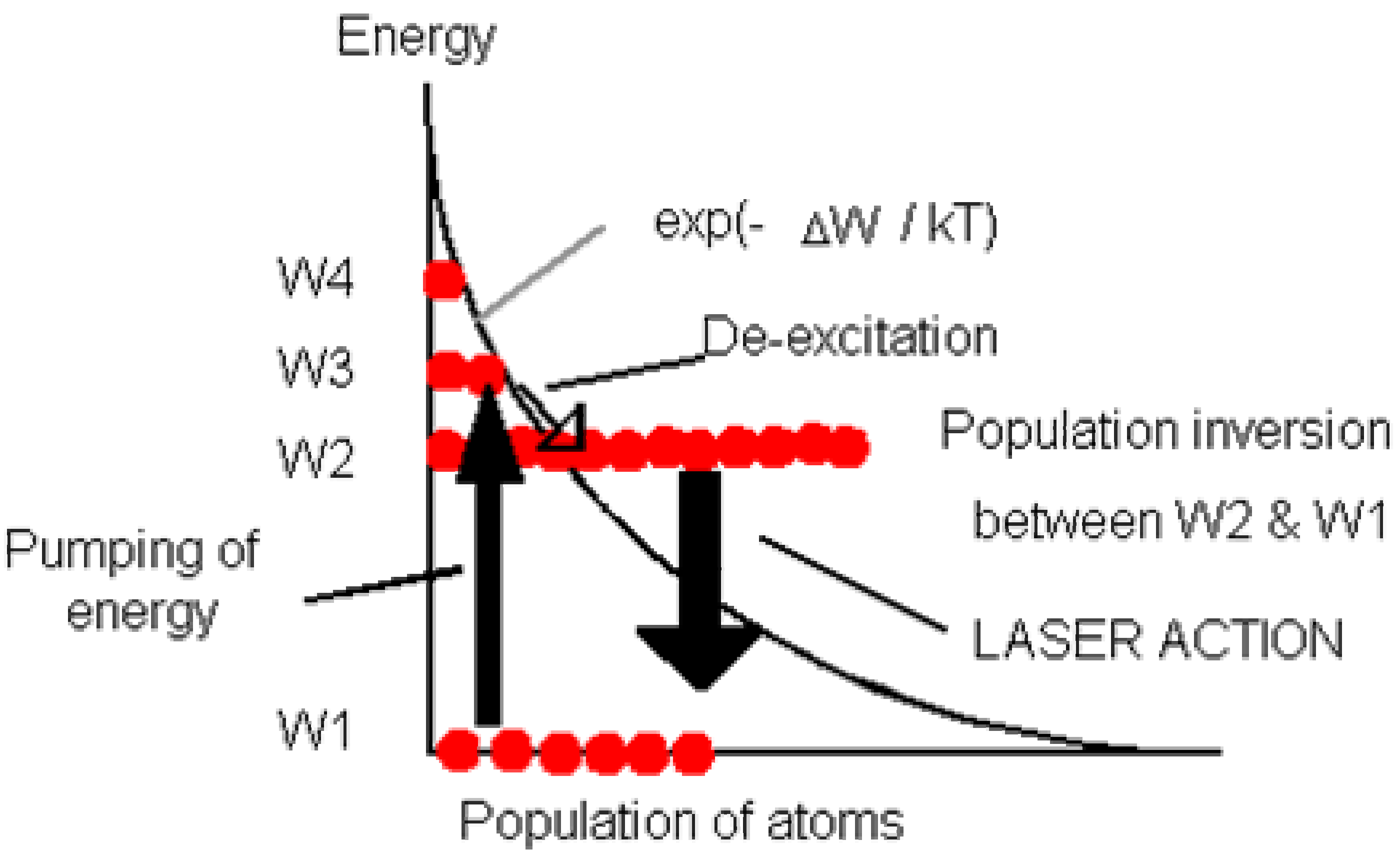
Figure 2.1-2: Absorption and emission of radiation

Principles of Laser

The stimulated photons have unique properties:It is in phase with the incident photon, it has the same wavelength as the incident photon and travels in same direction as incident photon

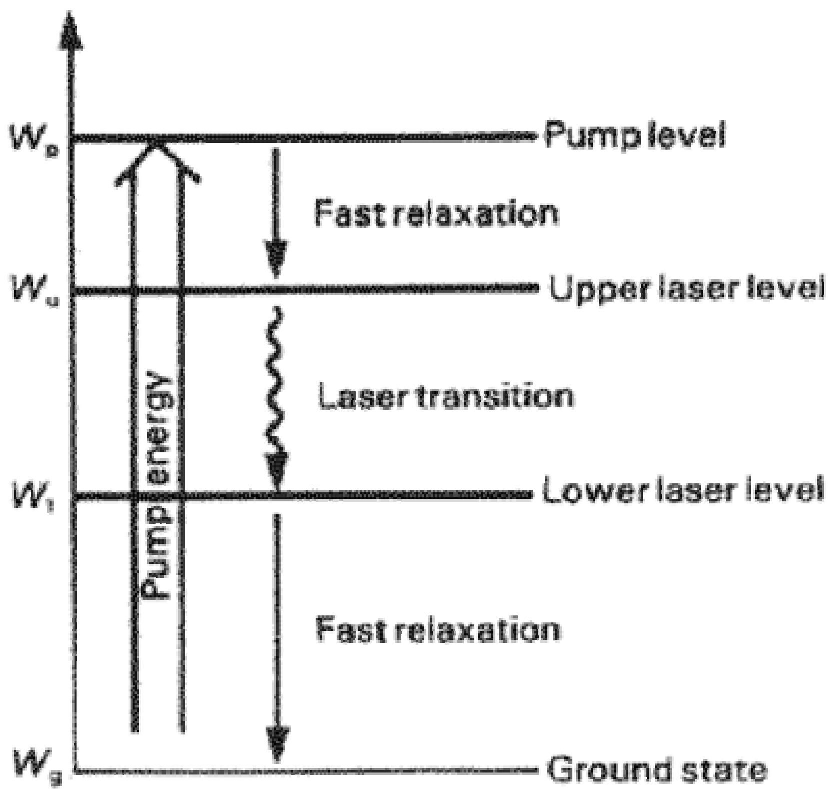
It is possible that the rate at which atoms are PUMPED into one of these states exceed the rate at which they leave. A large number of atoms can be excited into, and held in, the upper state leaving an almost empty state below them. Atoms can stay in this metastable state without de-exciting while the population is being built up this is known as a POPULATION INVERSION

Principles of Laser



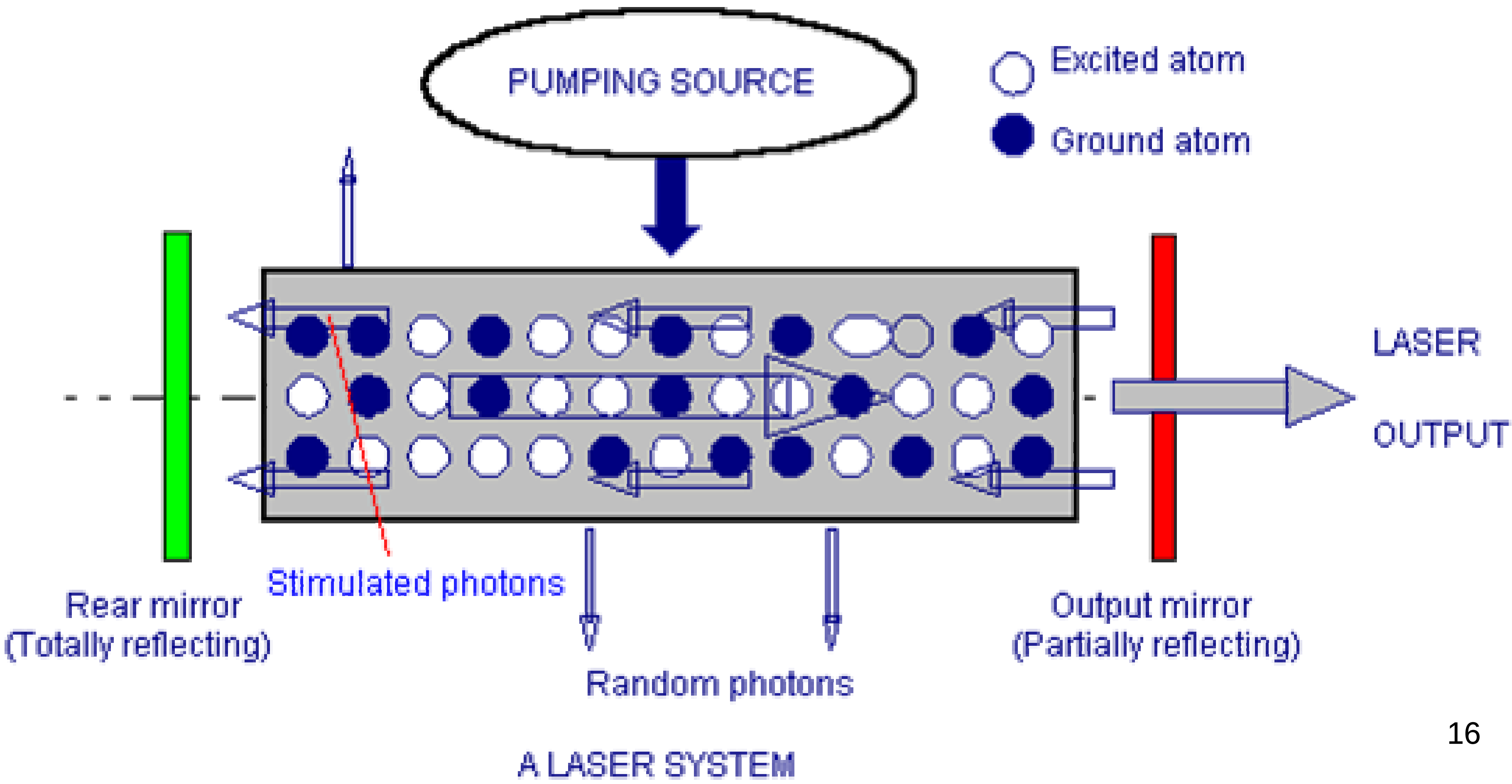
Principles of Laser

An improvement on this behaviour is obtained with a four-level structure where the laser transition takes place between the third and second excited states we need depopulation of the lower laser level to be rapid to ensure that the upper level is always full and the lower level always empty



Principles of Laser

In practice, photons need to be confined in the system to allow the number of photons created by stimulated emission to exceed all other mechanisms. This can be achieved by bounding the laser medium between two mirrors. this forms an OPTICAL RESONANT CAVITY one mirror is totally reflecting and the other partially reflecting.



Principles of Laser

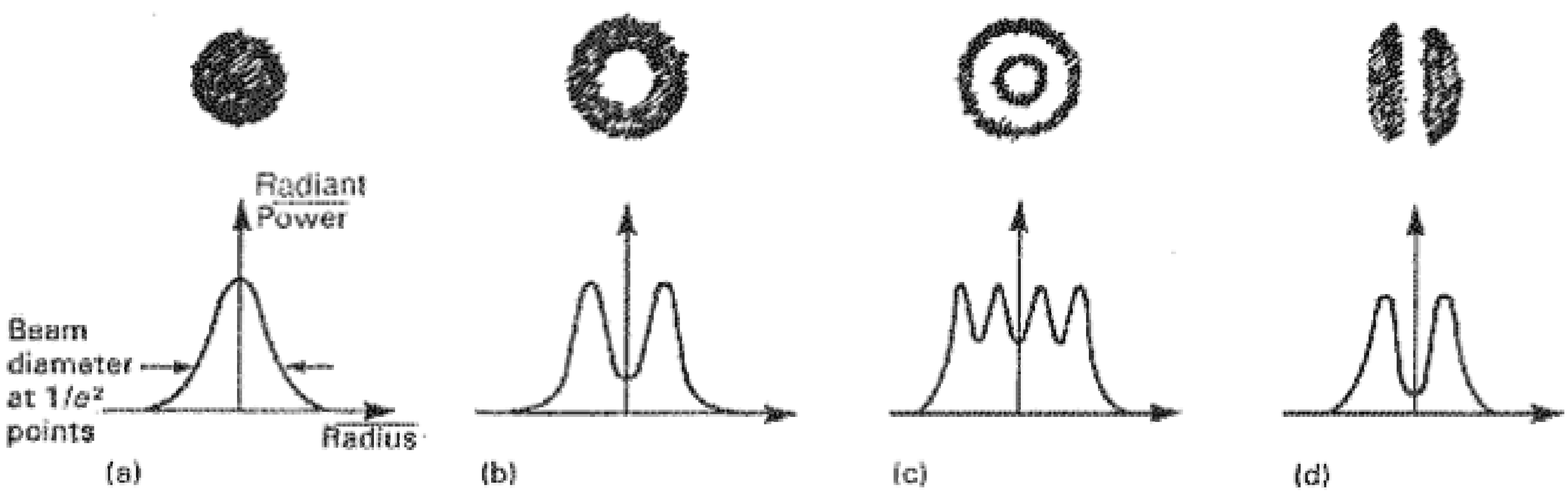
In an optical resonant *cavity* only specific LONGITUDINAL MODES OF OSCILLATION can be supported, which are like the standing waves on a stretched string pinned at both ends. Only those modes corresponding to multiples of *half a wavelength* can be supported and all other modes will die away.
This is also true in a laser cavity known as the LONGITUDINAL or AXIAL MODES of the cavity.

The cavity will have a finite width and will support TRANSVERSE modes arising from waves traveling off-axis along the cavity; these modes influence the *spatial* profile of the beam, which are defined in terms of the *T*ransverse *E*lectro*M*agnetic wave distribution across the cavity, *TEM* modes.

The FUNDAMENTAL mode is the TEM_{00} mode and corresponds to a smooth distribution of light across the output of the laser.

Principles of Laser

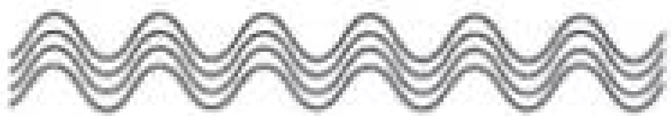
The transverse modes are a function of the cavity width



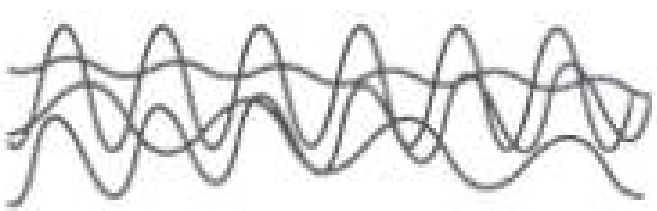
Properties of Laser Light

Monochromaticity: Laser light is concentrated in a narrow range of wavelengths lasers produce the purest (most MONOCHROMATIC) light available.

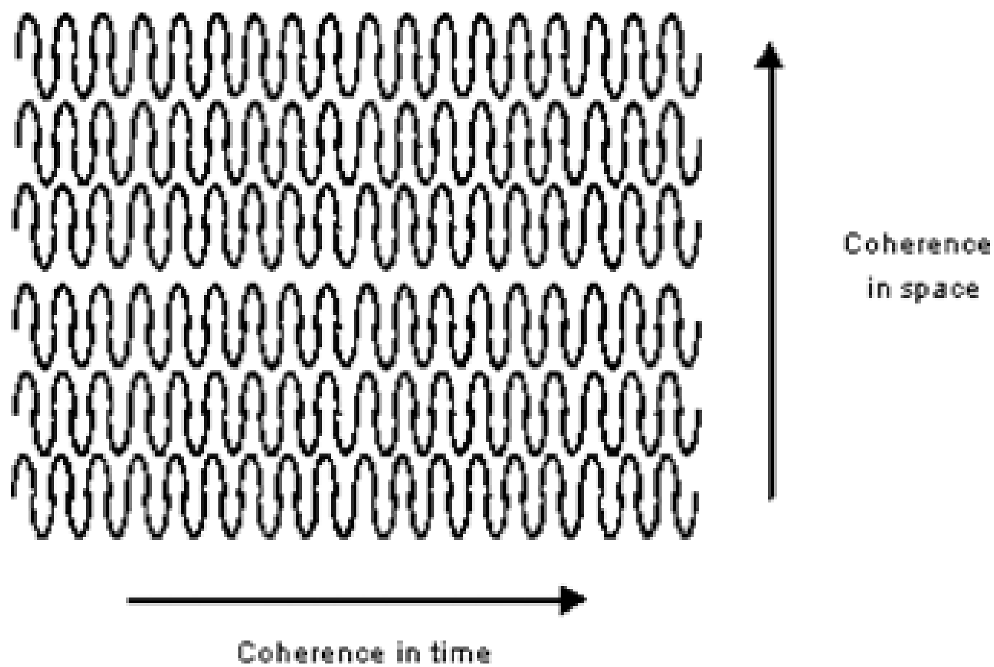
Coherence: All the emitted photons bear a constant phase relationship with each other in both time and phase the light is said to be COHERENT



(a) Coherent Light



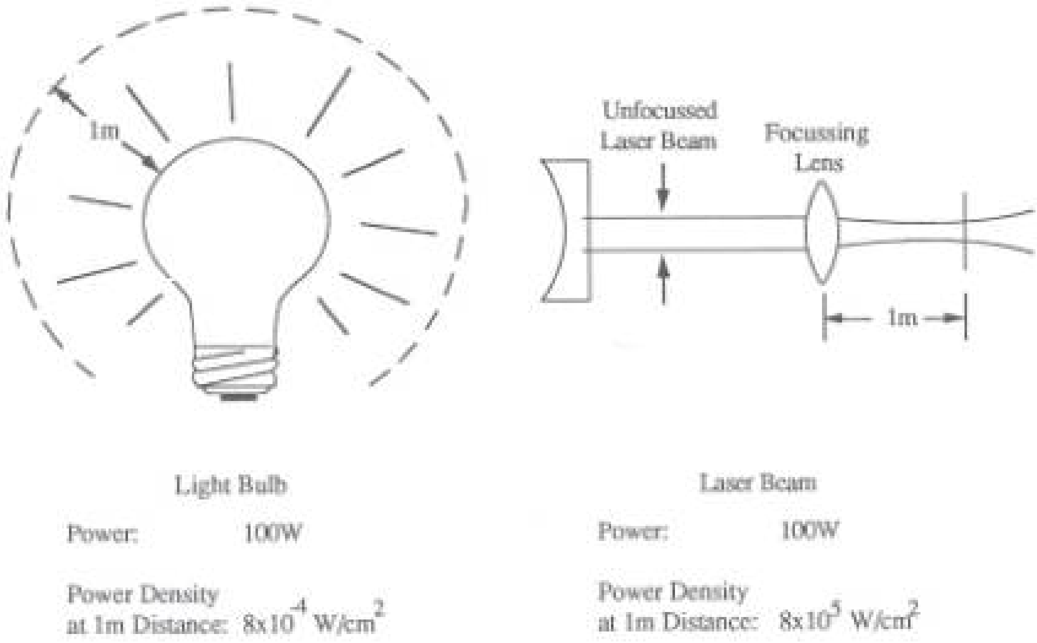
(b) Incoherent Light



Properties of Laser Light

Beam divergence: All photons travel in the same direction the light is contained in a very narrow pencil almost COLLIMATED laser light is low in divergence (usually).

High irradiance: Radiance is the amount of power per unit area emitted by a light source for a given solid angle, (in watts per square meter per radian). The solid angle can be thought of as a cone through which the light passes. The lasers have high power outputs for the small areas which is used to emit their beam of light. Thus, because lasers have low divergence, it causes a transmission over a small angle, producing a high radiance.



Practical Lasers

The basic requirements of any laser are similar, they all comprise of:

- An ACTIVE MEDIUM with a suitable set of energy levels to support laser action.
- A source of PUMPING ENERGY in order to establish a population inversion.
- An Optical cavity to introduce optical feedback so as to maintain the gain of the system above all losses.

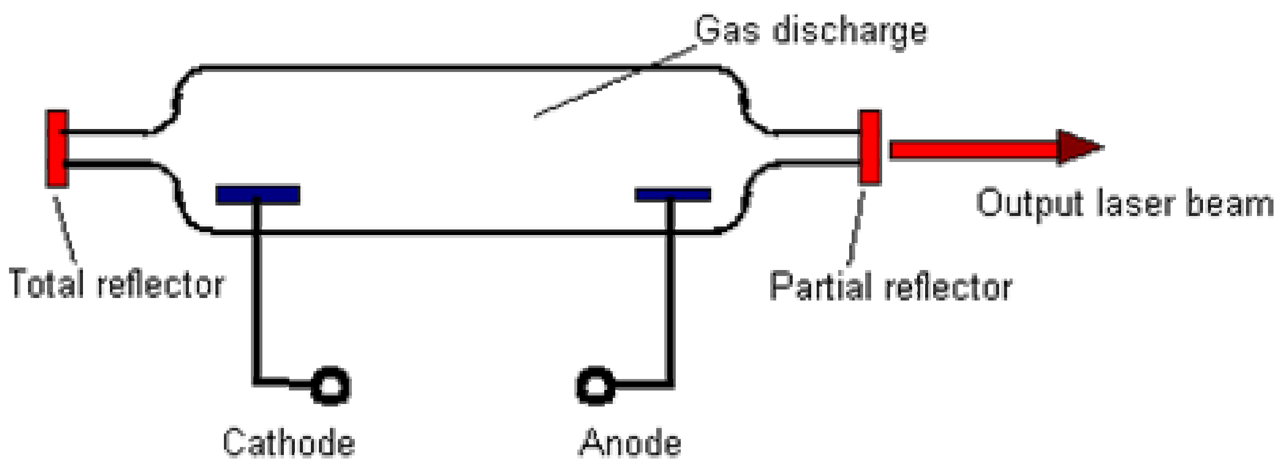
Lasers are usually classified in terms of their active (lasing) medium such as –

1. Solid state laser
2. Gas Lasers
3. Semiconductor lasers.

Gas Lasers

The Helium-Neon (HeNe) LASER

- The active laser medium is a gaseous mixture of He & Ne atoms, in a roughly 10:1 proportion.
- The gas is enclosed in a cylindrical quartz DISCHARGE tube sealed at each end by a mirror to form the optical cavity.
- Pumping is done via an electrical discharge (A GLOW DISCHARGE) created between the electrodes. A pulse of about 10 kV is applied across the electrodes to start the discharge.
- An electric current is induced through the gas; a steady current of 3 to 10 mA (dc) is sufficient to keep the discharge established.



TYPICAL GAS LASER

Gas Lasers

- The lighter He atoms are excited by collisions with electrons in the discharge. The He atoms collide with the heavier Ne atoms and transfer their energy to them. Ne atoms are excited by the collisions into their metastable state where population inversion builds up.

Laser light is emitted has wavelength of 633 nm (red), power in the range 0.5 to 50 mW; beam divergence about 1 mrad.

Gas Lasers

The Argon-ion Laser

- Unlike the HeNe laser, the active medium in the argon laser is a plasma of excited IONS.
- An electric discharge is created in a narrow tube of gaseous argon. The argon atoms are first ionized and then excited by multiple collisions with electrons into their upper energy levels.
- Due to the high energy required to ionize and excite the argon atoms very high current densities are needed, of the order of 1 A mm^{-2} .
- Argon lasers emit around 1 to 20 W of flux distributed amongst all the lasing wavelengths. 5 or 6 W can be obtained at the most powerful of these wavelengths, the 514 nm line.
- Common uses of argon lasers are holography, eye surgery, spectrochemistry, optical image processing, semiconductor processing and last, but not least in terms of numbers of lasers supplied, laser light shows.

Gas Lasers

The Carbon Dioxide Laser

- The important energy levels are provided not by the distribution of electrons but by the wiggling and jiggling of the entire carbon dioxide molecule itself.
- The CO_2 molecule can be pictured as a linear arrangement of O-C-O atoms which vibrate in relation to each other and several different modes of vibration give rise to a set of energy levels with transitions far into the infra-red.
- The principal CO_2 wavelength is 10.6 μm this is in the far infrared region of the spectrum.
- Continuous power outputs up to 25 kW are obtainable hence this laser is the favoured choice for materials-processing applications such as cutting, welding and annealing.
- Unlike most other gas lasers, the CO_2 has an appreciably high efficiency typically 10 to 15 %.
- To reach the high powers required from these lasers, cavity lengths can stretch to 2 or 3 meters or more.

Solid State Lasers

Solid State Lasers

•Solid state lasers are characterized by having as their active medium,a solid rod or slab of crystalline insulator doped with a small amount of impurity.

•To help avoid confusion in terminology with the SEMICONDUCTOR laser, solid state lasers are sometimes now referred to as DOPED INSULATOR LASERS.

•It is the impurity constituent which provides the required energy structure to produce laser action.

The Ruby Laser

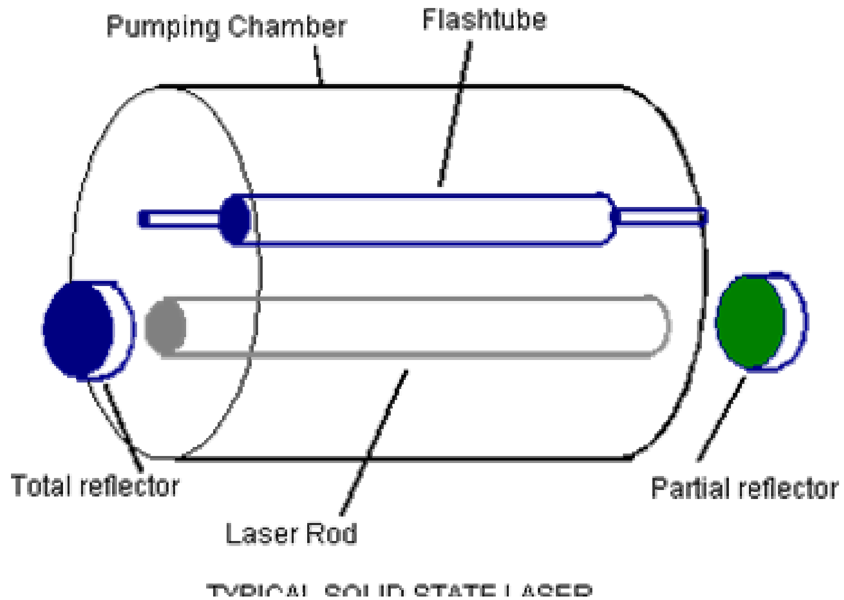
•The ruby laser takes its place in history by being the first working laser to be demonstrated.

•Theodore Maiman, working at Hughes Labs. In the USA, showed the first working laser to the world in 1960.

•The active medium is a cylindrical crystal of synthetic sapphire (Al_2O_3) doped with roughly 0.05%, by weight, of chromium ions (Cr^{3+}) RUBY.

Solid State Lasers

- The flatness over the entire end face of ruby rod should vary by no more than a quarter of a wavelength and both surfaces should be parallel to within a few seconds of arc.
- The ruby is irradiated by a short pulse of light from a xenon-filled flashtube. It absorbs pumping energy in the blue-green region of the spectrum and excites the chromium ions to the upper level of the laser transition. The principal laser energy emitted is of 694.3 nm wavelength
- Crystal and flashtube are placed parallel to each other within a polished pumping chamber ensures that as much light as possible is pumped into the rod.



Solid State Lasers

The Nd-YAG Laser

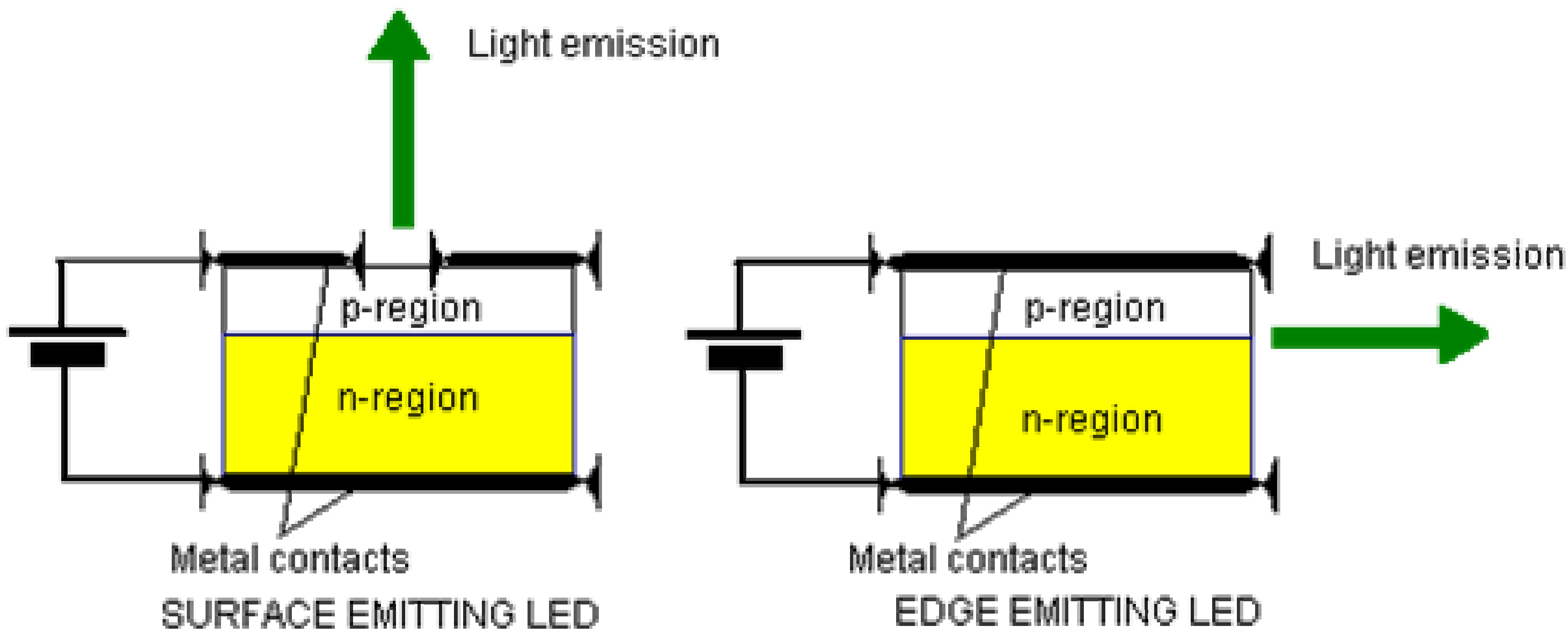
- Now supersedes the ruby as the most common doped insulator laser
- Host material is a crystal of yttrium-aluminium-garnate ($Y_3Al_5O_{12}$), YAG doped with 0.7% by weight of neodymium (Nd^{3+}) ions
- Laser emission takes place at 1.064 µm (infra-red)

Semi-conductor Lasers

SEMICONDUCTOR LASERS AND LIGHT EMITTING DIODES

- In a basic pn junction, free electrons in n-type diffuse into p-type under forward bias. In the p-region they meet a majority of holes & recombine and excess energy emitted as light.
- Typical emission wavelengths for LEDs

GaAs - 880 nm; GaP - 550 nm or 700 nm; GaAsP - 580 nm or 660 nm; Si - 1100 nm; Ge - 1810 nm.



Semiconductor lasers or Laser Diodes

• Formed from heavily doped pn-junctions based on modified light-emitting diode structure.

• To achieve laser action, need to ensure high concentration of e-h pairs available for recombination this is achieved by high doping concentrations across junction long spontaneous lifetime materials enhance stimulated emission.