

RECENT TRENDS IN PHYSICS: OPTICS & SPECTROSCOPY

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I. INTRODUCTION OF LASER FOR BEGINNERS

Introduction: The word **MASER** is an acronym that stands for **Microwave Amplification by Stimulated Emission of Radiation**. MASERs were invented in **1953** by two scientists, **Charles Townes** and **Arthur Schawlow**. **Microwaves** are a type of electromagnetic radiation that fall on the long wavelength side of the electromagnetic spectrum. Microwaves have a shorter wavelength than radio waves but a longer wavelength than visible light (λ : 4000 Å- 7000 Å). While considering the equilibrium between matter and radiation, **Einstein** found that the usual absorption and emission (now called, the spontaneous emission) processes alone were not sufficient to explain the equilibrium. Then he predicted a third process, called the stimulated emission. This work was paid little attention until 1954, when Townes and Gordon constructed a MASER by using ammonia (NH_3). Here, the stimulated emission occurs in the microwave region of electromagnetic spectrum so it is termed as the MASER.

Similarly, the word **LASER** is an acronym that stands for **Light Amplification by Stimulated Emission of Radiation**. In **1960**, the first fully functional LASER was completed by **Maiman**, but the technology of the LASER goes back to **Einstein's** study of **blackbody radiation** in 1917. Blackbody radiation refers to a cavity that absorbs all the radiation that falls upon it and re-emits part of this radiation in a proportion of quantized energy. **Max Planck** made this discovery. It was one of the founding discoveries in quantum physics (the physics of the subatomic world). This study of blackbody radiation led Einstein to discover the phenomenon of stimulated emission which is the main principle of how LASERs work. In 1961, **Ali Javan** (Bell Telephone Laboratories, USA) constructed the first gas laser (He-Ne laser). Scientists have found some radiations from the interstellar medium, whose intensities are so large that they can only be understood in terms of the masing action. After the discovery of the first molecule OH through its 18 cm radiation in the interstellar medium in

1963, this radiation of 18 cm in 1965 was found to show the maser action. After the OH molecule, H₂O molecule through its transition at 1.35 cm was found in 1969 to show the maser action. There are other molecules, such as SiO, CH₃OH etc. which show the maser action.

In LASERS, photons are interacted in three ways with the atoms: Absorption of radiation, Spontaneous emission and Stimulated emission. A LASER is emitted by the processes of population inversion in the system. A LASER system consists of three main constituents: working substance or gain medium, pump source and resonating cavity. On the basis of physical conditions of working substances are classified into three categories: (i) solid state LASERS (ii) liquid (or dye) state LASERS (iii) gaseous state LASERS. A LASER has following characteristics: (i) High directionality (ii) High Intensity (iii) Monochromaticity (iv) More Coherence.

Nowadays, we have a large number of lasers. These lasers have wide applications in our life. LASERS are used in various fields, e.g. in science and technology, communication, holography, industries, military, medical etc. It is an era of communication where LASERS are applied as a wave signal (message) which propagates in an optical fiber.

In brief we may say that A LASER is a device that amplifies light signal and produces a more coherent, more monochromatic, highly directional and highly intense beam. The size of a LASER varies from approximately 1/10 of diameter of a human hair to the size of a very large building, in power ranging from 10⁻⁹ W to 10²⁰ W and in the wavelength ranging from the microwave to the soft X-ray spectral region with corresponding to frequencies 10¹¹ Hz to 10¹⁷ Hz. LASERS have come out in the form of pulse (e.g. Solid State LASERS- Ruby LASER; pulse duration of the order of 10⁻¹⁵ s) or Continuous Wave form (e.g. Gaseous State LASERS-He-He LASER). LASERS can easily drill holes in the hardest materials and can weld detached retina within the human eye. LASERS are a main component of some of our most modern communication systems e.g. propagation of a LASER beam through an optical fiber and are of photograph needle. LASERS perform heat treatment of high strength material e.g. piston of our automobile engines and they behave as a special surgical knife in medical science. LASERS act as target designators for military weapons for the rapid check-out.

II. ATOMIC PROCESSES

Generally they are three:

- 1. Absorption process-**If in a system (e.g. atom, molecule and ion) electrons transfer from lower energy state say E_l to upper energy state E_u by themselves in the presence of a proper energy radiations (e.g. photon of frequency $\nu_{lu} = (E_u - E_l)/h$, where h is Planck's constant). In this process one photon is absorbed in transferring each electron (**Fig. 2.1a**).
- 2. Spontaneous emission of radiation-** If in a system (e.g. atom, molecule and ion) electrons transfer from upper energy state say E_u to lower energy state E_l by themselves after completing its (an electron) time in E_u state, the process is called spontaneous emission. In this process one photon of frequency $\nu_{ul} = \nu_{lu} = (E_u - E_l)/h$ is emitted in transferring each electron (**Fig. 2.1b**).

3. Spontaneous emission of radiation-If in a system (e.g. atom, molecule and ion) electrons transfer from upper energy state say E_u to lower energy state E_l by themselves in the presence of a proper energy radiations (e.g. photon of frequency $\nu_{ul} = \nu_{lu} = E_u - E_l/h$) during its (an electron) time in E_2 state, the process is called stimulated emission. In this process two coherent (i.e. same phase) photons are emitted in transferring each electron (**Fig. 1 c**).

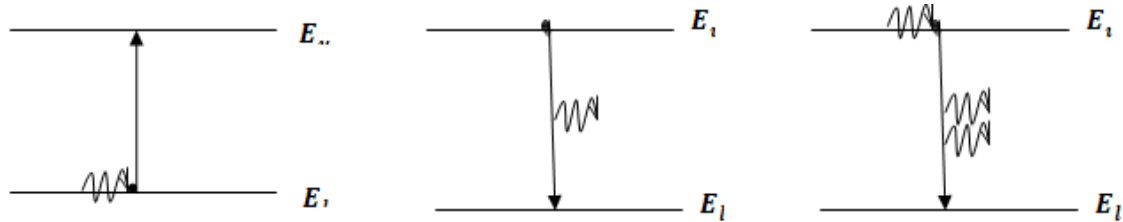


Figure 1: a- Absorption b- Spontaneous Emission c- Stimulated Emission

III. POPULATION INVERSION

In an atomic process the number of systems (e.g. electrons) decreases as the number of energy state increases. The number of system in i^{th} state is governed by **Maxwell Boltzmann’s distribution law** $N_i = N_0 e^{-E_i/k_B T}$, where E_i is energy of i^{th} state, $N_0 = N_1 + N_2 + N_3 + \dots$ is total number of systems, $k_B = 1.381 \times 10^{-23} J/K$ is Boltzmann’s constant and T is absolute temperature. The number of system corresponding to energy states E_1, E_2, E_3, \dots are given by:

$$N_1 = N_0 e^{-E_1/k_B T}$$

$$N_2 = N_0 e^{-E_2/k_B T}$$

$$N_3 = N_0 e^{-E_3/k_B T}$$

⋮

As $E_1 < E_2 < E_3, \dots$ so $N_1 > N_2 > N_3 \dots$

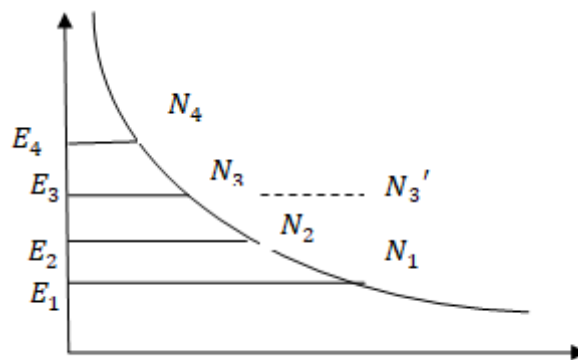


Figure 2: Population inversion

A process by which the number of system in a higher energy state becomes more than its lower energy state (e.g. $N_3' > N_2$) this process is known as **population inversion (Fig. 2)**.

The process to achieve the population inversion is called pumping. It is physical principle of a LASER. Pumping is following types:

1. **Optical Pumping:** In this type of pumping, optical lamp, e.g. xenon flash lamp is used in Ruby Laser and Nd: YAG LASER.
2. **Electrical Discharge or Direct Electron Excitation:** In this type of pumping, electrical discharge is used in Ar⁺ LASER
3. **Inelastic Atom- atom collision:** In this type of pumping, electrical discharge is used in He- Ne LASER
4. **Direction Conversion:** A direction conversion of electrical energy into radiant energy e.g. Light Emitting Diodes (LEDs).
5. **Chemical reaction:** In a chemical LASER energy comes from a chemical reaction. Example-H₂ + F₂ → 2HF + Energy is used to pump a CO₂ LASER.

IV. EINSTEIN'S A AND B COEFFICIENTS

We consider an atom having two states E_1 and E_2 which consists of N_1 and N_2 electrons per unit volume, respectively. The electrons in E_1 state can be transferred to E_2 state by absorbing a photon of proper energy radiation, i.e. $E_2 - E_1 = hv_{12}$.

Therefore, the rate of absorption per unit volume $\propto N_1 u(\nu)$,

Or, the rate of absorption = $B_{12} N_1 u(\nu) \dots (2.301)$

Similarly, we have the rate of stimulated emission per unit volume = $B_{21} N_2 u(\nu) \dots (2.302)$

The rate of spontaneous emission per unit volume = $A_{21} N_2 \dots (2.303)$

where $u(\nu)$ is energy density, B_{12} is Einstein's coefficient of absorption process, B_{21} is Einstein's coefficient of stimulated emission and A_{21} is Einstein's coefficient of spontaneous emission

In thermal equilibrium at temperature T; Net Rate of absorption = Net Rate of Emission

$$\text{Or, } B_{12} N_1 u(\nu) = B_{21} N_2 u(\nu) + A_{21} N_2 \Rightarrow u(\nu) = \frac{A_{21} N_2}{B_{12} N_1 - B_{21} N_2} = \frac{A_{21}}{B_{21} \left(\frac{B_{12} N_1}{B_{21} N_2} - 1 \right)} \dots (2.304)$$

From Maxwell- Boltzmann distribution law we have:

$$\frac{N_1}{N_2} = \frac{N_0 e^{-E_1/k_B T}}{N_0 e^{-E_2/k_B T}} = e^{(E_2 - E_1)/k_B T} = e^{hv_{12}/k_B T} \dots (2.305)$$

Using eq. (2.305) in eq.(2.304), we get:

$$u(\nu) = \frac{A_{21}}{B_{21} \left(\frac{B_{12}}{B_{21}} e^{hv_{12}/k_B T} - 1 \right)} \dots (2.306)$$

From Planck's theory of radiation, we have energy density:

$$u(\nu) = \frac{8\pi h \nu_{12}^3}{c^3 (1. e^{hv_{12}/k_B T} - 1)} \dots (i)$$

On equating the coefficient of eq. (2.306) and eq.(i), we get:

$$\Rightarrow \frac{A_{21}}{B_{21}} \propto \nu_{12}^3 \quad \boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu_{12}^3}{c^3}}$$

i.e. spontaneous emission is dominant over stimulated emission

$$\frac{B_{12}}{B_{21}} = 1, \text{ or } \boxed{B_{12} = B_{21}}$$

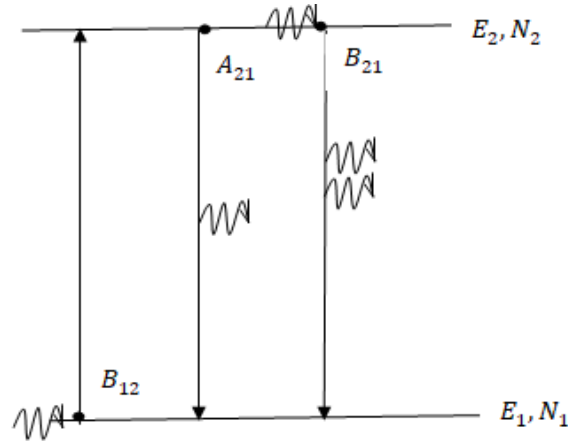


Figure 3: Einstein’s Coefficients

When an atomic system is in equilibrium state then the probabilities of absorption and stimulated emission are the same or in equilibrium both the processes take place side by side.

Therefore, $\frac{A_{21}}{B_{21}u(\nu)} = e^{h\nu_{12}/k_B T} - 1 \dots (2.307)$

When an atomic system is in thermal equilibrium at temperature T; for which $h\nu_{12} \ll k_B T$ then stimulated emission dominates over spontaneous emission. On the other hand when $h\nu_{12} \gg k_B T$ then spontaneous emission dominates over stimulated emission.

For an optically allowed transition, the radiative life-time T_u of upper level is the inverse of Einstein A-coefficient for the transition, i.e. $T_u = \frac{1}{\sum A_{ul}}$ when there is more than one downward radiative transition from the upper level.

V. MAIN COMPONENTS OF A LASER AND PRINCIPLE OF LASER ACTION-

The main component of a LASER are three:

1. **Working Substance** having meta- stable state having life time ($10^{-3}s$) which is more than life time ($10^{-8}s$) other higher states.
2. **Resonant Cavity-** It is a specially prepared cylindrical tube in which light intensity can build up by multiple reflections. The ends of the tube are silver polished, one end is completely silvered and other end is partially silvered so that an intense beam can come out from partially silvered end.
3. **Pumping system-** By which population inversion is achieved.

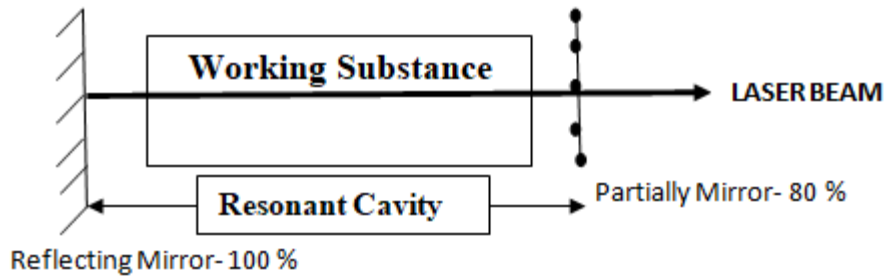


Figure 4: Main Components of a LASER

VI. CHARACTERISTICS OF A LASER BEAM

- 1. Highly directionality (or less divergence)**-The conventional light sources (e.g. Sun, burning candle, electric bulb or tube light etc.) or ordinary light sources (e.g. sodium lamp, mercury lamp, Xenon flash lamp, incandescent source, etc.) radiate light in all directions and show more beam divergence. Here, if we require a narrow beam, we get it to placing an aperture in front of the source whereas in case of LASER, the active medium or working substance is in the form of cylindrically resonant cavity. Here, any light which is not parallel to the axis of the cavity is eliminated and only the light come out which is parallel to the axis of the cavity constitute the LASER beam. Thus, the directionality of a beam may be expressed in terms of beam divergence. On the other hand, we may say that the output from a LASER is very close to an ideal uniform wave whose divergence is very small. Here, divergence occurs due to only diffraction. For a LASER oscillating in its lowest mode in its cavity, there would be approximately plane wave and showing spreading (or divergence) due to diffraction. The beam divergence increases with increasing power output and mode content. A LASER source emits light in direction or light from a LASER diverges very little. Thus, up to certain distance, a LASER beam remains a bundle of parallel rays, called **Rayleigh range** and the beam diverges beyond it (Fig. 2.5 a). The divergence depends upon two parameters (i) size of the beam (ii) diffraction.

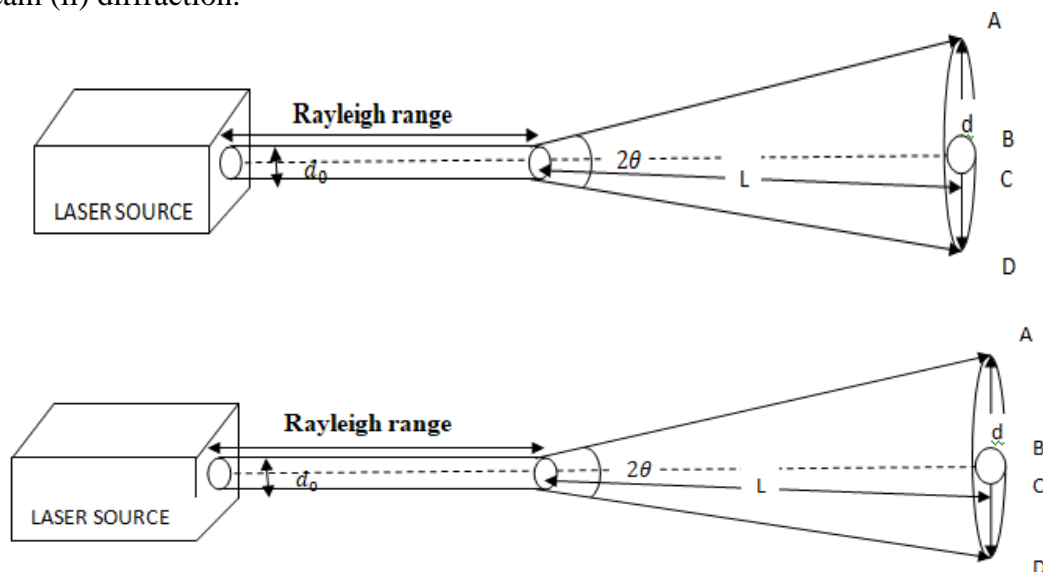


Figure 5 : a- Divergence of a LASER beam

$$\theta = \frac{AB (=CD)}{L} \dots (2.501) \Rightarrow AB (= CD) = L\theta$$

From the figure $AD = AB + BC + CD$ or, $d = L\theta + d_0 + L\theta = 2L\theta + d_0$

$$\text{or } \theta = \frac{d}{2L} - \frac{d_0}{2L} = \frac{r}{L} - \frac{r_0}{L} \Rightarrow \theta \approx \frac{r}{L} \dots (2.502), \text{ where } r \text{ and } r_0 \text{ are radii of the circles}$$

From the theory of diffraction the divergence $\dots (2.5i)$

$$2\theta = \frac{\lambda}{d_0}$$

Table 1: Divergence of LASERs Beams

Name of LASER BEAM	General Information	Beam Divergence 2θ (milli radian)
Ruby LASER (λ : 6929 Å & 6943 Å)	In 1960, Theodore Maiman invented 3 energy level solid state LASER: Less monochromatic & discontinuous or spiking	5
He- Ne LASER (λ = 6328 Å)	In 1961, Ali Javan & his coworkers invented 4- energy level gaseous LASER: more monochromatic & continuous	0.5
Fiber LASER (Ba crown glass doped with Nd ⁺ ion)	In 1961, Elias Snitzer	
Semi-Conductor LASER	In 1962, four independent group: used in now- a- days in fiber- optics communication	
CO ₂ (λ = 10.6 μ m)	In 1963, C.K.N. Patel	2
Ar ⁺ ion LASER (λ = 0.515 μ m)	In 1964, W. Bridges	0.8
Nd: YAG LSER (λ = 1.06 μ m & 1.318 μ m)	In 1964, J.E. Geusic & his coworkers , 4- energy level solid state LASER: Less monochromatic & discontinuous or spiking	
Neodymium glass Nd: Glass LASERs	Nd: Glass lasers are isotropic, which can be doped at high concentrations with excellent uniformity. Oxide glasses e.g. SiO ₂ and P ₂ O ₅ are the most common optical glasses that show lasing action. They are extremely high power, high energy multiple beam systems for inertial confinement fusion.	5
Liquid (Dye) LASER	Liquid (Dye) LASERs are similar to solid-state LASERs they consist of a host material (a solvent alcohol) in which the laser (dye) molecules are dissolved at a concentration of the order of 1 part in	2

	10,000. Continuous Wave dye lasers are mostly pumped by an Ar^+ LASER. Dye lasers cover a broad wavelength range from the ultraviolet (320 nm) to the infrared (1500 nm). A unique property of dye lasers is the broad emission spectrum (typically 30–60 nm)	
Gallium Arsenide Ga As LASER	Ga As is generally used in making of a solar cell, because it absorbs relatively more energy from the incident solar radiations having relatively higher absorption co-efficient.	4000

On account of high directionality of LASER beam it is possible to send direct a LASER beam to a far distant object and obtain its reflection of the same. **Example-**The distance between the Earth and the Moon has been correctly measured by directing He-Ne LASER beam to the moon and obtaining the reflection from a mirror placed on the Moon's surface by an astronaut. The time taken by the LASER beam to travel back and forth multiplied by the velocity of light gives the distance.

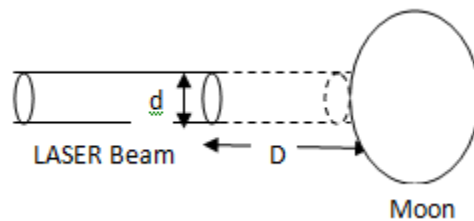
Example 2.501- A LASER beam of wavelength 6000 \AA on Earth is focused by a lens (or mirror) of diameter 2m on a crater on the Moon. The distance of the Moon from the Earth is $4 \times 10^8 \text{ m}$. How big is the spot on the Moon? Neglect the effect of Earth's atmosphere.

Solution 2.501- Given: $\lambda = 6000 \text{ \AA}$, diameter of the lens $d = 2 \text{ m}$, $D = 4 \times 10^8 \text{ m}$

$$\text{Angular spread } d\theta = \frac{\lambda}{d} = \frac{6 \times 10^{-7}}{2} = 3 \times 10^{-7} \text{ radian}$$

Area spread, i.e. area of the spot on the Moon

$$A = (D \times d\theta)^2 = (4 \times 10^8 \times 3 \times 10^{-7})^2 = 1.44 \times 10^4 \text{ m}^2$$



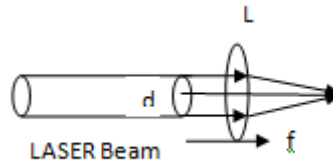
Example 2.502- A LASER beam has a power of 50 mW. It has an aperture $5 \times 10^{-7} \text{ m}$ and it emits light of wavelength 7200 \AA . The beam is focused with a lens of focal length 0.1 m. Calculate the area and the intensity of the image.

Solution 2.502- Given: $P = 50 \text{ m W}$, $d = 5 \times 10^{-7} \text{ m}$, $\lambda = 7200 \text{ \AA}$ and $f = 0.1 \text{ m}$

$$\text{Angular spread } d\theta = \frac{\lambda}{d} = \frac{72 \times 10^{-8}}{5 \times 10^{-7}} = 1.44 \times 10^{-7} \text{ radian}$$

$$\text{Area spread } A = (f \times d\theta)^2 = (0.1 \times 1.44 \times 10^{-7})^2 = 2.074 \times 10^{-10} \text{ m}^2$$

$$\text{Intensity } I = \frac{P}{A} = \frac{5 \times 10^{-2}}{2.074 \times 10^{-10}} = 2.4 \times 10^8 \text{ W/m}^2$$



2. High Intensity: Generally, the intensity of a light source at a point is defined as the energy passing normally per unit area per unit time for a point source. Intensity at a

distance 'r' from it is given by:
$$I = \frac{P(=\frac{W}{t})}{A_{spot}} = \frac{P}{\pi r^2} = \frac{P}{\pi(d/2)^2} = \frac{P}{0.785(f\theta)^2}$$

Where P is power radiated by the source, W is energy of the source and t is time, f is focal length of a lens and θ is angle of divergence.

In case of LASERS, the output power varies from mill watts to few kilowatts. Here, the energy is concentrated in a beam of very small cross section. The intensity of a LASER beam is given by:

$$I = \left(\frac{10}{\lambda}\right)^2 P \quad \dots (2.5 \text{ ii}) \text{ where } \lambda \text{ is wavelength of emitted light}$$

The intensity of a LASER beam is much more than the intensity of ordinary light sources.

Example 2.503- Calculate the intensity, energy and number of photons emitted per unit time of 1 mW He- Ne LASER source.

Solution 2.503- Given: $P_{He-Ne} = 1 \text{ mW} = 10^{-3} \text{ W}$

$$\therefore I_{He-Ne} = \left(\frac{10}{\lambda}\right)^2 P = \left(\frac{10}{6328 \times 10^{-10}}\right)^2 \times 10^{-3} = 2.5 \times 10^{11} \text{ W/m}^2$$

$$E = hv = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{6328 \times 10^{-10}} = 3.1413 \times 10^{-19} \text{ J}$$

$$\text{No. of photons emitted per unit time} = \frac{P}{hv} = \frac{10^{-3}}{3.1413 \times 10^{-19}} = 3.1834 \times 10^{18} \text{ S}^{-1}$$

3. Mono- chromaticity: Laser light is nearly mono- chromatic while light from an ordinary source is never mono- chromatic because in case of a LASER light spread (or line width $\Delta\lambda$) is very small (i.e. few Å) but in case of an ordinary light it is 100- 1000 Å. In other words, the line width of an individual cavity mode may be extremely small there may be many modes present in the LASER output. The high spectral purity, i.e. a very small line width of a LASER radiation leads to its applications in basic scientific research and engineering, e.g. photochemistry, luminescence excitation spectroscopy and communication etc. Degree of mono- chromaticity $\epsilon = \frac{\Delta\nu}{\nu_0} \Rightarrow \epsilon \propto \Delta\nu$, where $\Delta\nu$ is frequency spread of the spectral line of central frequency ν_0 . Thus, smaller the value of ϵ , higher the value of mono- chromaticity, e.g. $\epsilon_{LASER} \approx 10^{-12}$ and $\epsilon_{ordinary \text{ light source}} \approx 10^{-5}$.

4. Coherency: For discuss interference; we defined coherence between two sources of light consisting of a constant phase difference. In a light source the light we observe is the resultant of radiations emitted by billions of atoms, molecules or ions of the source. The atoms, molecules or ions operate independently of one another. An individual atom does not emit radiations continuously but only suddenly due to incident of proper energy photon, the system transfers from upper energy level to lower energy level through stimulated emission. In this process two photos are emitted which are coherent. To what extent the radiations from different atoms of a given source may be coherent with respect to space and time. Thus, coherence are two types (i) **Temporal Coherence** (ii) **Spatial Coherence**.

- **Temporal Coherence:** A perfect coherent source emits sinusoidal wave which is the function of time whereas there is no source which can produce sinusoidal wave all the time. It is due to the reason, that an excited atom in the process of returning to its initial state emits light pulse of short duration of the order of 10^{-10} s, after which the phase changes (**Fig. 2.5 b**) abruptly. The average time interval for which **the electric field** which is dominant to the magnetic field in an electromagnetic radiation (e.g. light) remains sinusoidal is called **temporal coherence**.

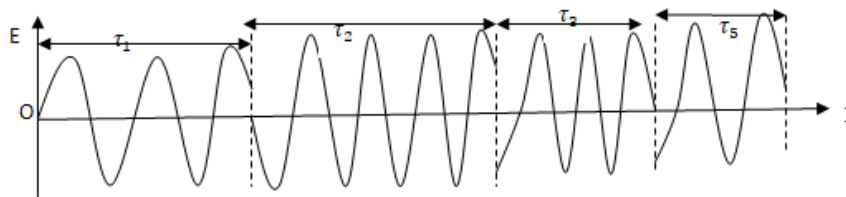


Figure 5 : b- Temporal coherence

Coherence time τ_{coh} - The average time for which the field remains sinusoidal is called coherence time, i.e. $\tau_{coh} = \frac{\sum_{i=1}^n \tau_i}{n} = \frac{\tau_1 + \tau_2 + \tau_3 + \tau_4 + \dots}{n}$

Coherence length L_{Coh} - The distance for which the field remains sinusoidal is called coherence length. i.e. $L_{Coh} = c \tau_{coh}$

Table 2

Light Source (Color)	Coherence length L_{Coh}	Coherence time τ_{coh}	Purity of spectral line $Q = \lambda/\Delta\lambda$
Sodium (Yellow)	3 cm	10^{-10} s	10^5
Cadmium (Red)	30 cm	10^{-9} s	10^6

Examples- Temporal coherence exists in Michelson Interferometer

Spatial Coherence- The spatial coherence is the phase relationship between the radiation fields at different points in space. Spatial coherence length is expressed as:

$$L_{\omega} = \frac{\lambda d}{a} = \frac{\lambda}{\theta}$$

where a is width of a single slit, d is separation between the two slits.

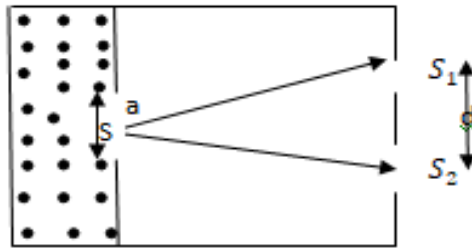


Figure 5: c- Spatial Coherence

In **Fig 5 c** the dots denote the excited atoms emit light of wavelength λ . If $\angle S_1SS_2 = \theta < \frac{\lambda}{a}$ then both the slits S_1 and S_2 receives light from each of the emitter atoms and thus will be in coherence.

Examples: Young's double slit or Fresnel's bi- prism experiment in interference

Example 2.504: The coherence length for sodium light is $2.945 \times 10^2 \text{ m}$ and the wavelength of sodium light is 5890 \AA . Calculate: (i) the number of oscillations corresponding to the coherence length (ii) coherence time.

Solution 2.504- Given: $L_{coh} = 2.945 \times 10^2 \text{ m}$, $\lambda = 5890 \text{ \AA}$

- No. of oscillations corresponding to the coherence length $n = \frac{L_{coh}}{\lambda} = \frac{2.945 \times 10^2}{5890 \times 10^{-10}} = 5 \times 10^4$
- Coherence time $\tau_{coh} = \frac{L_{coh}}{c} = \frac{2.945 \times 10^2}{3 \times 10^8} = 9.82 \times 10^{-11} \text{ s}$

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